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The Land Use Sequence Optimiser (LUSO): A theoretical framework for analysing crop sequences in response to nitrogen, disease and weed populations

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Abstract. The break crop effect, where a non-cereal crop provides relief from soil pathogens, may increase soil nitrogen reserves for a cereal and help minimise populations of herbicide resistant weeds. It is widely used in agriculture to maximise the economic return and yield of cereal crops. In Western Australia, cereal crops are being grown with increasing frequency, at the expense of less profitable break crops and we have developed a land use sequence optimiser (LUSO) to analyse strategic break crop decisions across a suite of price, yield, nitrogen fertiliser cost, soil borne disease load and weed load thresholds. The model is flexible and can easily be parameterised for a wide range of economic, edaphic and biotic parameters. We demonstrate its use in a strategic sense to determine economic and biotic thresholds that force a rotation change in a typical Western Australian cropping system.

Additional keywords: crop sequence, rotation, weeds, disease, optimisation.

Introduction

Crop rotation or land use sequencing is used in agriculture to manage edaphic and biotic processes that reduce the yield of the dominant crop. Farmers have used crop sequencing to manage soil borne disease, weed populations, stored soil moisture, nitrogen status and nitrogen and carbon cycling to ensure crops continuously reach their potential yield. Despite the benefits of crop rotation, farmers need to maximise their economic return over a sustained period and this complicates the decision to grow a particular crop. A variety of approaches have been developed to help farmers make this decision.

Many of the edaphic and biotic processes that influence crop yield have been synthesised into crop models such as APSIM (Keating *et al*. 2003), DSSAT (Bowen *et al*. 1998) and Century (Parton *et al*. 1994). These models are capable of simulating crop yield in different crop sequences and routinely identify a 'sequence effect' where one crop alters the edaphic and biotic environment, thereby influencing the yield of the subsequent crop. For example, Dolling *et al*. (2005) demonstrated that lucerne dries the soil profile more than a cereal or legume crop and this can reduce the yield of cereals grown after lucerne. DSSAT has been used to explore the impact of water stress in rice–wheat rotations (Timsina and Humphreys 2006) and soybean-corn rotations (Saseendran *et al*. 2007). The models can be used to explore productivity and sustainability issues (Probert *et al*. 1998) and have been used to track the long-term environmental effects that rotations have on carbon, nitrogen, cover and drainage levels (Robertson *et al*. 2009). However, the rotation studies conducted with such simulation models have not considered important biotic factors such as the accumulation of soil borne disease and weeds, and their effect on crop yield.

Empirical approaches have been used to model crop sequences, where the biotic factors governing crop yield are represented simply as an effect on crop yield, ignoring the underlying biology. Some dynamic crop sequence models such as RIM (Ryegrass Integrated Management model) retain some biological function. RIM predicts the economic outcome of a set rotation in response to the build up of herbicide resistant weed populations that 'damage' the yield of the crop and can account for weed effects; however, the model cannot be optimised (Monjardino *et al*. 2004; Pannell *et al*. 2004).

Empirical whole-farm and field-level models that evaluate crop rotation decisions have been developed, where the external factors that influence crop yield are incorporated into the rotation models. The ROTAT model developed by Dogliotti *et al*. (2003), calculates an optimal outcome given a series of constraints and rotation choices. The model may be parameterised using expert knowledge, farmer information or historical experiments to determine a 'break crop effect'. This approach is also used in the MIDAS (Model of an Integrated Dryland Agricultural System) whole farm bioeconomic model, where

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every crop rotation must be defined and different crop rotations elicit a yield 'boost' entered by the user (Kingwell and Pannell 1987). Detlefsen and Jensen (2007) represented crop sequences as a series of network flows, while Castellazzi *et al*. (2008) systematically represented sequence choices as a heuristic that can be used to deduce important factors, such as the return time for a particular crop. In the cases mentioned, the user must assume or define a break crop effect, which typically affects only the single following year. The user must also define other rotation rules.

Unfortunately, a 'break crop effect' can be difficult to define or quantify. Disease and seasonal effects on wheat crop yields have been captured in a regression equation by Roget and Rovira (1991), but have not been incorporated into crop sequence models or crop simulation models. Kirkegaard *et al*. (2008) noted that, on average, a break crop can improve the yield of the subsequent cereal by ~14% in North America, 33% in Southern Australia and 24% in North Europe. However, the size of the break crop effect varies between studies and the basis for this variation may be due to the interplay between disease population dynamics, nitrogen cycling, climate and the potential yield of the cereal crop.

Crop simulation models are too complex to be optimised and often ignore disease and weed effects, while empirical models invariably rely on expert opinion or the results of a limited number of site specific trials to predict the break crop effect. We argue that there is a need for a crop sequence model that is simple enough to be optimised, but still captures the important biotic processes of weed population dynamics, disease population dynamics, and nitrogen accumulation that influence future crop yield. The model must also accommodate economic factors such as commodity price. Furthermore, the model should represent the long-term multi-year nature of these processes, rather than over-simplify them to a single-year aggregated 'break-crop effect'.

To cope with this problem, we have developed a modelling approach where the model can be optimised and quickly parameterised for any expected seasonal and price situation. We demonstrate the capabilities of this flexible modelling framework, with sensitivity analyses to address three questions: (*i*) What biological characteristics must be present to ensure wheat can be grown at high frequency (>50%) in a cropping sequence; (*ii*) What price and yield combinations of break crops must be achieved before either canola or lupins are included in a crop sequence with cereals; and (*iii*) What sequences are selected when nitrogen prices reach extreme levels? We show that for each of these questions, LUSO can be used to evaluate sequences across a full range of biological and price extremes to determine which sequence gives the best profit over a series of years, given a particular set of prices, starting conditions and biological parameters. These simulations demonstrate the novelty, flexibility and power of LUSO.

Methods

Model overview

The objective of the model is to maximise the economic return from a sequence of crops through time, in response to weed, disease and nitrogen status. The model operates on an annual time step and the economic return from each crop is influenced by the weed population, disease population and nitrogen level at the time of planting. In addition, the crop influences these populations and the nitrogen status for the subsequent crop. To avoid the complexity of possible seasonal variation in factors such as potential yield, weed and disease population dynamics and nitrogen mineralisation, and the extreme difficulty of predicting such seasonal effects many years in advance, this version of the LUSO model follows many other well established models (e.g. Kingwell and Pannell 1987; Pannell *et al*. 2004) in assuming an average season throughout the sequence.

Diseases, weeds and nitrogen all influence crop yield and the model is constructed around the notion that weeds and disease 'damage' yield, as proposed by Cousens *et al*. (1987). The model includes a yield damage function with weed and disease components. These components are calculated in weed and disease sub modules that simulate population dynamics over the duration of the simulated period. In addition, each crop has a nitrogen requirement. This can be supplied entirely from external sources at a cost. Alternatively, a legume crop or pasture can supply part of this requirement, thereby reducing the cost of production of the following crop.

A profit is determined for each year, where this profit depends on both the chosen land use and the state of the system, and where the state of the system consists of the weed seedbank density, the disease burden, and the soil nitrogen status at the start of a year.

Thus the current land use choice indirectly influences the economic return that can be derived from all future land use choices. Unlike most other models, the dynamic weed and disease populations enable the model to capture a break crop effect beyond a single year.

Nitrogen module

The objective of the nitrogen module is to capture and represent the nitrogen contribution a legume crop makes to the following crop as a fertiliser equivalent. The module implicitly accounts for the nitrogen fixed by the legume and this is represented as a fertiliser saving for the following cereal crop. Each crop has a certain nitrogen requirement Nr. Assuming a tonne of wheat removes 20 kg N (12% protein) and this represents 50% of total plant N (Halloran and Lee 1979), we assume wheat requires 160 kg N/ha to produce a 3 t/ha crop and canola requires 120 kg N/ha to grow a 1.3 t/ha crop. The lupin and pasture options do not require nitrogen fertiliser. In this model, it is assumed the nitrogen requirements for the crop are met with soil nitrogen, which has no cost, and nitrogen fertiliser.

In the model, nitrogen accumulates in the soil when lupins are grown and harvested, lupins are grown and green manured, or if a pasture (assumed to be legume dominant) is grown. The model only takes into account nitrogen that is available for use by the following crop. Using values derived from the 'select your nitrogen', (SYN) (Bowden 2003), which is calibrated from data compiled by Evans *et al*. (2001), it is assumed that this nitrogen accumulates in the soil (Nb) at 50 kg/t of lupin grain yield, 70 kg/t of potential lupin grain yield when lupins are manured and 35 kg/t of biomass produced by the pasture.

These three options have a potential yield (y_p) of 1.5, 1.7 and 3 t/ha and, if these yields are obtained, will thus contribute 75 kg/ha, 119 kg/ha and 105 kg/ha respectively to the soil for the following crop. We assume that nitrogen does not accumulate if wheat or canola is grown. The total soil nitrogen Ns at the end of a year is thus equal to $Nb \times y_p$, where Nb is the nitrogen 'boost' to the soil per tonne of potential yield for the crop (or pasture) that was grown, and y_p is the potential yield.

Additional nitrogen fertiliser costs ($Ncost$) \$/kg, so growing legumes reduces the input cost in the following cereal or oilseed crop. The default cost of nitrogen in this simulation was \$2/kg. Cereal and oilseed crops are assumed to use all available nitrogen from the previous year, so if these crops are then grown again in the following year, all the nitrogen must be supplied as fertiliser. The total cost for nitrogen in a given year (Cn) is given by the following equation:

$$Cn = \begin{cases} Ncost(Nr - Nb \times y_p) & \text{if} \quad Nr > Nb \times y_p \\ 0 & \text{if} \quad Nr \leq Nb \times y_p \end{cases} \tag{1}$$

which simplifies to $Ncost$ (Nr–Ns) if $Nr > Ns$ and 0 if $Nr \leq 0$, where Ns is the amount of soil nitrogen provided by the previous crop, as described above.

Weed module

The weed module is based on the RIM model of annual ryegrass (*Lolium rigidum*) seedbank dynamics (Pannell *et al*. 2004). At the start of each year, it has a dormant weed seed bank, which in the first year is set to 50 seeds/ha. A fixed proportion of the weed seeds germinate (p_g, default value 0.8) and then the land use choice dictates what percentage of these weeds survive to set seed (p_s, default value 0.05). For example, if we start with 50 seeds at the beginning of year one, under default values 40 seeds will germinate and two of these weeds will survive to set seed. The seeds that did not germinate carry over into the seedbank in the following year. The number of seeds produced by the surviving weeds is determined by the well established hyperbolic function (Cousens *et al*. 1987). This equation can be written as:

$$\text{Seedset} = \frac{SS_{\max} k_w d_w}{1 + k_w d_w + k_c d_c} \tag{2}$$

where *Seedset* is the actual number of weed seeds produced (per m^2), $SS_{\max}$ is a model parameter representing the theoretical maximum weed seed set possible (seeds/m^2, default value 30 000), k_w is a model parameter representing the size or competitiveness of the weed (default value 1/33), k_c is a model parameter representing the size or competitiveness of the crop species, which depends on the land use, d_w is the weed density (plants/m^2), which varies from year to year, and d_c is the crop density (plants/m^2), which depends on the land use. A proportion p_r of this set seed is assumed to be returned to the seedbank, and the value of this parameter depends on the current land use. The full equation that maps the seed bank density from one year to the next is:

$$sb_{n+1} = (1 - p_g)sb_n + p_r \frac{SS_{\max} k_w (p_g p_s sb_n)}{1 + k_w (p_g p_s sb_n) + k_c d_c} \tag{3}$$

where sb_n is the seed bank density at the start of year n. The default parameter values for the weed are taken from the RIM model, and represent ryegrass. However, they can easily be varied to represent other weeds. The default parameter values for the different crops are also taken from the RIM model (Pannell *et al*. 2004).

The hyperbolic function described above is also modified to give the multiplication factor for the effect of weed competition on crop yield (wcf),

$$wcf = 1 - \frac{k_c d_c}{1 + k_w d_w + k_c d_c} \tag{4}$$

The value of wcf will always be between zero and one, and it will be closer to one when weed density is high and closer to zero when weed density is low.

Disease module

Cereal crop options harbour cereal soil disease, while legume and oilseed crops reduce the extent of the cereal disease population. Cereal disease burden is represented as a value (d) between 0% and 100%. However, if the disease burden exceeded 50%, it was reset to this value as this was close to the maximum yield penalty (53%) that take-all was found to inflict on wheat (Roget and Rovira 1991). It is assumed that the system begins with a basal level of disease (3% default). The level of cereal disease changes from year to year via a disease multiplier (dm) that is dependent on the land use. By default, non-cereal crops (legumes or oilseeds) and legume pastures have negative disease multipliers. This returns the disease level to a basal level of 1% for the subsequent crop. However, this can be adjusted if required; for example, a positive multiplier could be used to represent a pasture with a mix of grass weeds that carry cereal disease. The cereal disease dynamics are described by the equation:

$$d_{n+1} = \begin{cases} d_n \times dm & & dm > 0 \\ 0.01 & \text{if} & dm \leq 0 \\ 0.5 & & d_n \times dm > 0.5 \end{cases} \tag{5}$$

The effect of the cereal disease on the crop is represented by the disease damage factor (ddf), which in turn depends on the cereal disease level d and the crop's resilience to cereal disease (s), according to the equation:

$$ddf = d \times s \tag{6}$$

Note that like the weed competition factor wcf, ddf always lies between zero and one, and will take values close to one when disease level and susceptibility are high, and take values close to zero when disease level or susceptibility are low. The effect of cereal disease in a system can be explored by varying the crop's resilience to disease (s) and varying the crop's ability to propagate disease (dm). Cereal leaf diseases are not considered in this version of LUSO.

Canola disease (such as blackleg) is also included in the model. This works in a very simple way, where it is assumed that if a canola crop is followed by another canola crop in the subsequent year, then the yield of the second canola crop will be reduced by 80%. Diseases of legumes are not currently included in the model.

Module synthesis and economics

The yield of a crop (*Yeq*) is a function of the weed damage function (*wcf*) and the disease damage function (*ddf*), defined previously:

$$y_a = y_p \times (1 - ddf) \times (1 - wcf) \quad (7)$$

where y_a is the actual or achieved yield and y_p is the potential yield, which depends on the current land use (crop). Soil nitrogen level does not affect yield as it assumed that nitrogen requirements are always satisfied by either nitrogen available from the previous crop, or from bought fertiliser. It is assumed the crop will always be supplied with required nitrogen, but the amount of nitrogen supplied through fertiliser will affect the variable costs associated with crop production. In turn, the current crop influences future nitrogen status, weed population and disease status in subsequent crops. In the current version of the model, for the sake of simplicity, system state variables do not directly affect one another. For example, soil nitrogen status does not affect the weed population, weed numbers do not affect disease status, and the effects of weeds and disease on yield do not reduce the nitrogen boost for the following crop. However, the model is written in a modular way that would facilitate adding these kinds of interactions in the future if required.

To account for the fact that the weed seedbank remaining at the end of the simulated sequence will have a negative effect on future profits related to its size, we introduced a penalty of \$*WScost* per seed for each weed seed in the final seedbank. We did not introduce a similar penalty for the final disease burden or a value for any final soil nitrogen because these are shorter-term issues than weeds, but these could easily be introduced in the future if required.

The profit in a given year depends on the actual yield y_a, as well as the annualised fixed costs, which do not depend on the current land use, and the variable costs and product price (value), which do depend on the current land use. Profit in future years is discounted, so that the net present value of a sequence is calculated as:

$$\sum_{n=0}^{Y}((y_a p_{i_n} - Cf - Cv_{i_n} - Ncost(Nr_{i_n} - Ns_{i_n}))(1 - dis)^{n-1}) - WScost \times sb_Y \quad (8)$$

where n is the year of the sequence, Y is the total number of years in the sequence, i_n is the land use chosen in year n, p_i is the price received per yielded tonne of the product of land use i, Cf is the fixed cost per hectare, Cv_i is the variable cost for land use i, excluding nitrogen, *Ncost* is the per unit cost of nitrogen in fertiliser form, Nr_i is the units of nitrogen required for land use i, Ns is the current units of nitrogen in the soil, *dis* is the discount rate, *WScost* is the assumed cost of a weed seed remaining in the seedbank and sb_Y is the final weed seedbank density.

Initial parameter values for the simulation are presented in Table 1.

Sequence sensitivity to nitrogen, disease and weed pressures

In this sensitivity analysis, 1296 simulations were conducted where prices and yields remained constant but the six parameters with biological meaning, nitrogen cost (Nitrogen cost), pasture disease multiplier (pdm), wheat disease multiplier (wdm), wheat disease effect (wde), weed survival in wheat (wws), and the wheat competition index (wci) were all varied in a nested array. The interactions between all six variables were captured in the simulation. Under default price and yield scenarios (wheat yield 3 t/ha, wheat price \$350/t, canola yield 1.3 t/ha, canola price \$550/t, lupin yield 1.5 t/ha and lupin price \$250/t), sequences were generated where Nitrogen cost varied from \$1.50 to \$4.00/kg, wheat disease multiplier varied from 1 to 4, the wheat disease effect varied from 0.5 to 1.0, the pasture disease multiplier varied from –1 to 0.5, weed seed survival varied from 0.2% to 0.5%, wheat competition index ranged from 0.1 to 0.08 and the pasture disease multiplier ranged from –1 to 0.5. The complete suites of biophysical simulations are described in Table 2.

The sensitivity analysis around biophysical parameters was conducted to determine when a biophysical variable will force a change in the sequence. This sensitivity analysis allows the true cost of managing weeds, disease or nitrogen to be calculated over the life of the sequence.

Extreme values of all six parameters were chosen that collectively represent a benign cropping environment where the wheat disease multiplier was 1 and the weed seed survival 0.2%, an aggressive weed and benign disease system where the disease multiplier was 1 and the weed seed survival level was 0.5%, a benign weed seed survival rate (0.2%) and aggressive disease system (4), and finally an aggressive weed seed survival rate (0.5%) and aggressive disease system (4).

Sequence sensitivity to yield and price

3072 simulations were conducted where the yield and price of the different crops were varied in a nested array under the default biological scenarios (Nitrogen cost = 2, weed seed survival = 0.05, crop multiplier = 4, crop competition index = 0.9). Sequences were generated where price and yield for the three crops varied from \$400 to \$700/ha for canola, \$250 to \$550/ha for wheat and \$200 to \$350/ha for lupins. Yields ranged from 1.0 t/ha to 1.9 t/ha for canola, 2.1 t/ha to 3.0 t/ha for wheat and 1.0 t/ha to 1.9 t/ha for lupins. This array of price and yield combinations generated a suite of yield × price ratios between all three crops. The array of yield and price combinations also affects the scale of economic damage weeds, disease and nitrogen can inflict on the system, as a greater loss is incurred when damage affects a high value crop. The vast array of combinations evaluated can be simplified into three scenarios; high wheat returns with a low canola or lupin return; uniform return across all crops and finally, high returns from canola or lupins with a low return for cereals.

Results

Effect of biological processes on a continuous wheat sequence

The four biological extremes of the weed seed survival rate and disease population multiplier affected the wheat yield through time. The benign system barely influenced wheat yields. In contrast, when the weed seed survival rate increased from 2% to 5%, wheat yields declined from 3 t/ha to 2.1 t/ha at the end of

Table 1. Initial and default conditions for simulations, default economic and nitrogen attributes, and default disease, weed and crop competition attributes

Parameter	Symbol	Start value
Initial and default conditions for simulations		
Length of sequence (years)	y	6
Seedbank population at year 0	sb_0	50
Weed germination (%)	p_g	0.8
Weed competition index	k_w	0.0303
Weed maximum seedset	SS_{max}	30 000
Nitrogen cost ($/kg)	$Ncost$	2
Soil nitrogen	Ns_0	0
Soil disease population at year 0	d_0	0.03
Fixed costs accrued per ha every year	Cf	150
Discount rate	dis	0.05
Cost per weed seed	$WScost$	0.1
Season	n	0

Land use	Potential yield (y_p) (t/ha)	Price (p) ($/t)	Variable cost (Cv) ($/ha)	N requirement (Nr) (kg/ha)	Nitrogen boost per tonne of crop grown (Nb)
Default economic and nitrogen attributes					
Wheat	3.0	350	200	160	0
Lupins harvested	1.6	275	200	0	50
Sprayed pasture	3.0	0	100	0	25[A]
Canola	1.3	550	250	120	0
Lupins manured	1.6	0	150	0	70

Land use	Disease multiplier[B] (dm)	Disease effect on crop (s)	Weed seed survival (p_s)	Competition index (k_c)	Sowing density (plants/m^2) (d_c)	Weed seed return (p_r)
Default disease, weed and crop competition attributes						
Wheat	4	1	0.05	0.09	150	1.0
Lupins harvested	–1	0	0.03	0.08	40	1.0
Sprayed pasture	–1	0	0.03	0.08	50	0.1
Canola	–1	0	0.03	0.08	100	1.0
Lupins manured	–1	0	0.03	0.08	40	0.1

[A]Nitrogen boost for pasture relates to the amount produced per tonne of biomass.
[B]Negative disease multiplier returns the disease population to the default level.

Table 2. Sensitivity analysis of biophysical attributes

Variable[A]				
Nitrogen cost ($/kg)	1.5	2	3	4
Disease multiplier (Pasture)	–1	0.2	0.5	
Disease multiplier (Wheat)	1	2	3	4
Disease effect (Wheat)	0.5	0.75	1	
Weed seed survival (Wheat)	0.02	0.035	0.05	
Competition index (Wheat)	0.08	0.09	1.0	

[A]The crop type that influences or is influenced by the variable is included in brackets.

the six year sequence. When the weed seed survival rate was benign (2%), but the disease multiplier was aggressive (4), wheat crop yields declined to 1.5 t/ha after three years of continuous wheat and then plateaued to 1.4 t/ha. Wheat yields declined to 1.2 t/ha after six years when both the weed seed bank and disease multiplier were aggressive.

Sensitivity analysis to variations in nitrogen cost, weed and disease status

Optimal profit after six cropping seasons ranged from $298 to $2333 where between three and six crops of any species were grown. This range of scenarios demonstrates the model's ability to value the effect of weeds and disease beyond the damage caused to a single crop in one year. In all, 29 different sequences were selected out of the theoretical pool of 15 625.

Biophysical environments conducive to continuous cropping

Continuous cropping with wheat, lupins or canola was only selected when weeds could be successfully controlled. This option was selected in 28% of the 1296 scenarios evaluated. Three different types of continuous cropping sequences were selected. Continuous wheat (8.5% in total) was only selected in a benign cropping environment where weed seed survival was at its lowest (0.2), the wheat disease multiplier was at its lowest at 1, ensuring disease populations remained static, and the disease effect on the crop was very low (0.2 or 0.35). Continuous wheat was selected in these conditions even when nitrogen costs increased to $3/kg and implies that nitrogen price had only a small effect on the sequence relative to other parameters. Continuous wheat, if selected, was the most profitable sequence.

Wheat was grown in sequence with canola (8.5% of sequences) if the annual weed survival was low (0.2) and the cost of nitrogen fertiliser was low ($1.50/kg). Canola was only selected in the sequence one year out of six and in the remaining five seasons, wheat was selected. Lupins were grown in sequence with wheat (11.2% of sequences) if nitrogen costs exceeded $1.50/kg and the weed survival multiplier was low (0.2). Continuous cropping, where all six crops were harvested, was not selected as a sequence if weeds became a problem. The lupin and canola crops were able to minimise the impact of the wheat disease multiplier at moderate and high levels (2, 3, 4). Three of the four most profitable sequences were continuously cropped and they were profitable because income was generated in every year of the sequence.

Sequences for hostile cropping environments

Continuous cropping was not selected in any of the more hostile cropping environments where the wheat disease multiplier was at the highest level (4) and the weed survival was also high (0.05). These 108 scenarios were the most hostile simulated, and nine different sequences were selected for these environments that, depending on the other four variables, generated profits of between $298 and $1357 over the life of the sequence. Thus, hostile environments generated returns that were at least $978 lower than environments with low disease and weed levels. These sequences can be grouped into three sub categories, three wheat with three lupins manured; four wheat with either two lupins manured, two pastures sprayed or one of each; and five wheat with either a lupin manured or pasture sprayed option. The pasture and manured lupin options generate a negative return, and profit was only generated by the cereal. As a result, the dominant economic driver in hostile cropping environments was the frequency that a cereal could be grown. In these environments, the cereal suffered damage through weeds and disease. When nitrogen costs were high, the legumes were manured. This strategy minimised the cost of nitrogen and kept weed and disease populations low. If nitrogen costs decreased to $1.50/kg or $2/kg and pasture provided an effective disease break, it was included in preference to a manured lupin as it was cheaper to implement. However, if the pasture was unable to provide this disease break, lupins were included in the sequence as a manure crop. In hostile environments, the break crop that provided the most successful break by lowering weed and disease status was selected over the other alternative. This allowed the most valuable crop to be grown in the following season.

Sequences with high nitrogen prices

Nitrogen influences overall profit more than any other variable (Fig. 1). When nitrogen was set to $4/kg, approximately double the current market rate, only three possible sequences were selected even though 324 scenarios were evaluated by varying the five other variables. In these three sequences, three wheat crops were grown and three lupin crops were grown. The most profitable situations, where two lupin crops were harvested, occurred when the weed survival levels were at their lowest (0.2) and the wheat competition index was at its highest. If the

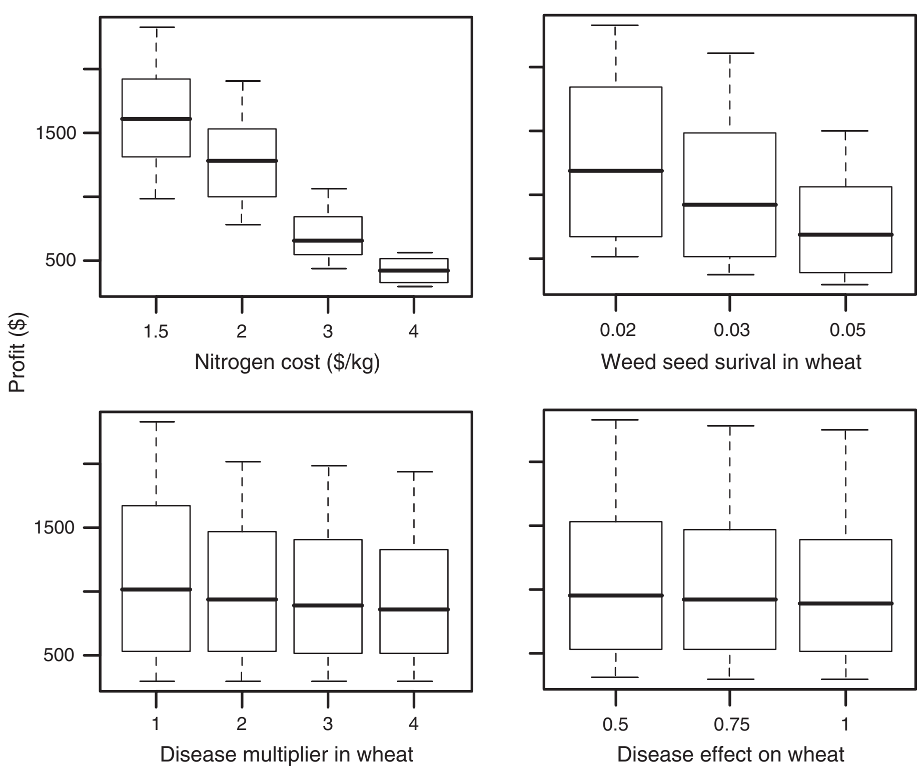

Fig. 1. Effect of nitrogen price, weed seed survival and disease multiplier and disease effect on whole of sequence profitability.

weed competition index declined, a lupin crop was manured, and if the weed seed survival increased from 0.35 to 0.5, then all the lupin crops were manured. Thus, if nitrogen costs escalate, legume frequency increases. If weeds cannot be controlled, then the legume crop may be manured to keep the weeds under control, but the return from the sequence declines from $566 when two lupin crops are harvested to just $346 if one lupin crop is harvested and $298 if all three lupin crops are manured over the six year period.

In summary, LUSO attempts to grow the most valuable crop as frequently as possible while ensuring factors that limit yield do not swamp the expected yield. It does not grow a combination of crops of lower value.

Price ratio between crops

The price scenarios in Table 3 generated profits that ranged from $-714 to $3278 in a six year sequence. Twenty different sequences were selected for the 3072 price by yield scenarios evaluated. Wheat dominant sequences were common. Wheat was sown either four or five times in 53.4% of scenarios where sprayed pasture provided the only break (45.4%) or provided the break in conjunction with a canola crop (8%). Of the 20 sequences selected, just four featured prominently and these accounted for 66% of all price–yield scenarios. The most common (four wheat, two sprayed pasture) accounted for 32% of all scenarios and returned between $193 and $1928. The next most common (three canola, one harvested lupin crop and one sprayed pasture) accounted for 11.9% of all sequences and generated profits from $-660 to $1772. The other two common sequences included three canola crops, and a wheat crop grown with two sprayed pastures that generated from $322 to $1738 and finally, five wheat crops grown with a sprayed pasture that generated between $2449 and $3099. Sprayed pasture was included in all four of these sequences.

Wheat was selected, with a sprayed pasture break, when an alternative could not be profitably grown, relative to wheat. The frequency that wheat was grown in the sequence was directly influenced by the relationship between wheat yield by price combination and the yield by price combination of a suitable break crop. Wheat frequency generally increased as the ratio between wheat price and yield and that of the break crop exceeded 1 (Fig. 2). The frequency of harvested break crops in the sequence generally increased if their yield by price combination approached or exceeded 1. If a break crop could not generate a significant return in its own right, it was excluded from the sequence.

Table 3. Sensitivity analysis of economic attributes

Crop	Yield (t/ha)			
Canola	1.0	1.3[A]	1.6	1.9
Wheat	2.1	2.4	2.7	3.0[A]
Lupin	1.0	1.3	1.6[A]	1.9
	Price ($/t)			
Lupin	200	275[A]	350	
Wheat	250	350[A]	450	550
Canola	400	500[A]	600	700

[A]Indicates the default setting.

Discussion

The modelling framework developed here has been used to strategically assess what sequences can be implemented in a field under any given set of conditions. It maximises profit by maintaining soil-borne disease populations and weed populations at economic levels over many years and ensures the long-term sustainability of the cropping sequence. It can be used to predict the profitability of a particular cropping sequence for a set of biophysical and economic conditions and will determine which cropping sequence is optimal for these conditions. It can be used to predict how the profitability of a particular sequence changes in response to changes in the key biophysical or economic components of the farming system. It can also be used to test how the optimal sequence will change given changes in these biophysical or economic components.

The model has been designed for rapid calibration to determine the most profitable field level sequence over as short or long a time frame as necessary. New crops that provide a weed or disease break can be easily incorporated into the model. Rapid changes in price can be accommodated and the parameters used in the biophysical components can be altered according to the region or seasonal forecast. Alternatively the biophysical components may be calibrated directly from experimental data.

Key biophysical processes that influence crop yield via a damage function have been included in this model. Similarly, RIM (Pannell *et al.* 2004) includes some biophysical mechanisms and crop damage functions are routinely used to assess and model the effect weeds have on crop yields (Cousens *et al.* 1987). By including these biophysical functions, the long-term cost of weeds and disease can be accounted for in the farming system. To parameterise the model for new weed species or new diseases, some understanding of the biophysical processes will be required. These processes will need to be modelled and incorporated into the crop damage function. Disease models that operate on an intra-annual time step that model monocyclic or polycyclic

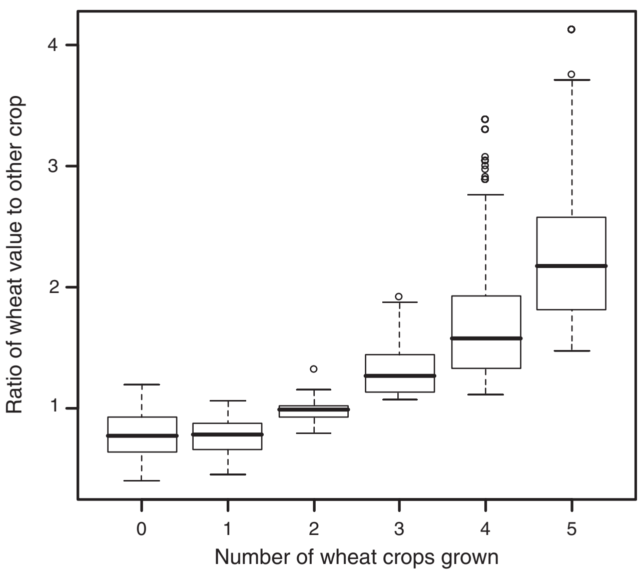

Fig. 2. Wheat crop frequency *v.* ratio of wheat value to break crop value in a six year sequence.

disease populations could be used to inform the disease parameters embedded in LUSO. Alternatively, data from detailed disease studies (e.g. Gutteridge and Hornby 2003; Li *et al*. 2006) or historical analysis of crop sequencing trials (e.g. Seymour 2009) could be used. This contrasts with other farm scale sequence models such as ROTAT and MIDAS that rely on expert opinion to estimate the magnitude of a single aggregated 'break crop effect' on a cereal crop (Kingwell and Pannell 1987; Dogliotti *et. al.* 2003).

Crop sequences are inherently complex, but the model has been constructed so it can be parameterised for a given situation quickly. For example, a multitude of sequence and crop choices exist in the Western Australian wheatbelt, which encompasses 20 million hectares between 300 and 500 mm rainfall isohyets on soil types ranging from deep acid sands to alkaline clay loams. Crop options may be limited to one or two cereal crops in some portions of the wheatbelt, while in others, canola, faba beans, lupins and field peas can all be grown. In addition, the disease threat varies; the importance of certain diseases varies from region to region according to rainfall, soil type and crop management (Yeates *et al*. 1986; Salam *et al*. 2002). In contrast, herbicide resistant weed populations are ubiquitous across rainfall and soil type gradients at low levels (~1 plant/m^2) (Llewellyn *et al*. 2009). The model framework can be quickly parameterised for local conditions in any location of interest and updated with appropriate yields and current prices. Existing models, such as MIDAS and RIM, cannot be recalibrated quickly to deal with these dynamic system and price fluctuations because they depend on a much larger number of parameters.

The model has been primarily designed for researchers and consultants to help quantify system level benefits associated with a particular component of the model. For example, the model could be used to evaluate the economic impact of improved disease tolerance in cereals or the improved yields of break crops for low rainfall regions. LUSO can account for complex long-term temporal processes, which is important because many of the economic effects associated with break crops accrue over several seasons. Thus, like MIDAS, LUSO was not developed as a farmer decision support system (Pannell 1996), but rather as a tool to evaluate the outcomes of different research paths and direct research and extension efforts to deliver the greatest economic benefit to growers.

We exploited the simplicity of the framework to perform a large number of simulations across a suite of biological and price scenarios. These sensitivity analyses demonstrated that when nitrogen price doubled, the frequency of legumes in the sequence did increase, although smaller, and arguably more sensible movements in fertiliser price had little impact on the sequence. Sensitivity analyses were performed on variables across an extreme range of parameters using the modelling framework presented here. In a complex model, where simulations take time to build, run and process, the value of conducting simulations with data extremes may be questionable. However, we have demonstrated that in this framework, such a simulation can be performed quickly and efficiently and system tipping points, such as the high nitrogen price or level of weed seed survival, can be quickly identified. It may be impractical to quickly re-run optimisation analyses based on complex simulations when prices or costs change, but we have shown that a simple dynamic model such as LUSO can cope with these fluctuations because it is relatively easy to change parameter values and re-run the optimisation. The need to quickly perform analyses of this type is likely to increase if the volatility of input prices, grain prices and grain yields continues.

Possible changes in climate may affect yield and some of the biophysical components in the model. Complex systems models that integrate disease and weeds cannot be quickly calibrated, yet coefficients of simple models can be altered and sequences formulated to cope with best and worst case scenarios. In addition, system changes, such as a new weed or disease entering the system, can be efficiently modelled using the approach described. All of these scenarios affect agriculture in a dramatic fashion and decisions need to be made quickly and efficiently. Simple models can often provide fast and efficient solutions using cut down or simple representations of otherwise complex biological processes.

Simplifying representations of processes within models always involves tradeoffs. By assuming an average season in all years, we may not be taking account of important drivers of land-use sequencing. For example, the choice of whether or not to grow a crop in a given year might depend on whether there is sufficient stored soil moisture from summer rainfall. The rate of disease or weed population growth might depend on the season rainfall or temperature patterns. The amount of nitrogen available to the following crop might depend on mineralisation rates, which in turn depends on weather conditions. We propose that a new model based on the approach taken with LUSO but incorporating seasonal weather variability could be constructed, and would provide important new insights and capabilities.

In conclusion, we have constructed a Land Use Sequence Optimiser capable of evaluating land use sequences, finding the most profitable sequence in a given situation, and testing the sensitivity of the solution found to changes in prices, costs and biophysical factors. We have explained that it can be quickly calibrated for new regions, weed species, or diseases, or to take into account changes in costs, commodity prices, or even potential yields due to climate change. We have demonstrated LUSO's capabilities by performing a series of analyses that suggested the crop that generates the maximum return should be grown as frequently as possible; the place of alternative crops in optimal sequences depends mainly on their ability to manage weeds and diseases; and using ungrazed well managed pasture as a 'break-crop' is likely to result in a more profitable system than using alternative crops such as canola or lupins unless the returns generated by these alternative crops are similar to the return generated by the primary crop. We argue that LUSO finds a new balance between complexity and simplicity. It achieves this by combining sub-modules representing soil nitrogen and the multi-year population dynamics of weeds and disease and representing these processes as simply as possible. This balance allows important processes affecting the long-term profitability of land-use sequences to be incorporated into the model, while ensuring the exhaustive factorial analyses, optimisation and quick re-parameterisation can be performed. This is what makes LUSO a tool with great potential for addressing a wide range of questions and issues concerning land-use sequencing in agricultural systems.

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