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Steven Schilizzi, David Pannell

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Steven SCHILIZZI*, David J. PANNELL

Agriculture & Resource Economics, University of Western Australia, Crawley (Perth) WA 6009, Australia

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Abstract – This paper investigates the economic value of nitrogen fixation in a Mediterranean-type farming system in Western Australia, as well as a general approach to such an investigation. The method uses linear programming and is exemplified by the MIDAS model developed in Western Australia. MIDAS is an optimisation model that describes key bioeconomic interactions at the paddock and whole-farm levels. The value of nitrogen thus depends on its capacity to generate farm profits. The value of fixed nitrogen then depends on the economic value of the fixation agent (typically a legume) and its place in the farming system, on the proportion of fixed and applied nitrogen in the system, and on the bioeconomic interactions between the two forms of nitrogen. Of course, soil type and climate also affect the value of nitrogen, but so do fertiliser and crop and animal prices, as well as their seasonal variability.

nitrogen fixation / economics / legumes / farming systems

Résumé – **L'économie de la fixation d'azote.** Cet article examine la valeur économique de la fixation d'azote dans un système de production de type méditerranéen, l'agriculture de l'Australie Occidentale, ainsi qu'une méthode générale pour une telle étude. La méthode utilise la programmation linéaire et est représentée par le modèle MIDAS développé en Australie Occidentale. MIDAS est un modèle d'optimisation qui décrit les principales interactions bioéconomiques à l'échelle de la parcelle et de l'exploitation agricole. La valeur de l'azote dépend de sa capacité à générer pour l'exploitant des bénéfices économiques. La valeur de l'azote fixé dépend alors de l'agent fixateur (typiquement des légumineuses) et de sa place dans le système de production, de la proportion d'azote fixé et épandu, et des interactions entre les deux formes d'azote. Bien entendu, le type de sol et le climat affectent aussi la valeur de l'azote, mais également le prix des engrais et des produits tant végétaux qu'animaux, ainsi que leur variabilité saisonnière.

fixation d'azote / économie / légumineuses / système de production

1. INTRODUCTION

Nitrogen is a key input to most crops and pastures that do not belong to the leguminous family. Because nitrogen in its various forms is usually costly, it is an important decision for farmers to provide it to their crops in the most economic way. In particular, they may have to choose between chemical fertilisers and legumes to provide the nitrogen. Of course, there are various types of fertilisers with different nutrient mixes, and there are different species of legume crops and pastures. However, the primary question farmers may ask is, which of fertilisers and legumes provide nitrogen in the most economic way? To answer this question, we must first decide what it is to be economic. Farmers operating in a market economy will value nitrogen depending on how it

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* Correspondence and reprints
Steven.Schilizzi@uwa.edu.au

can improve their income and, in particular, the profitability of their farming enterprise. The value of nitrogen will thus be defined as a function of its capacity to contribute to farm profits. How is this to be done in practice? And can the value of nitrogen fixation be separated, not only from the total amount of nitrogen provided, but from the value of legumes? This paper examines these questions in the light of particular examples and from a more general methodological point of view. For it turns out that the answer is not simple and is costly to obtain.

This paper focuses not on the value of nitrogen in general, but on the value of nitrogen fixed by leguminous plants. As a corollary, part of the value of legumes will reside in their capacity to fix atmospheric nitrogen. It is immediately obvious that the value of fixed nitrogen cannot be computed "in general" but will strongly depend on how it fits into a farming system. If value is to be defined with reference to farm profits, then different legumes that fetch different market prices, have different productivity parameters, or entail different production costs, will all differently affect the value of nitrogen fixation. This is because to provide this form of nitrogen farmers need to invest in the production of these legumes. If the value of fixed nitrogen is too low, or its production costs are too high, then it may be more economic to resort to chemical fertilisers or, in more extreme cases, not to provide any nitrogen at all.

2. THE GROUNDS FOR VALUING NITROGEN FIXATION

The value of nitrogen fixation rests on two fundamental economic concepts: marginal value and opportunity cost.

Marginal value is important because of the law of diminishing marginal returns. Figure 1 shows a typical yield to nitrogen response function in a dryland Australian wheatbelt environment (300–500 mm rain per year), defined on a fixed (per hectare) area. When the initial quantity of nitrogen available to the farming enterprise (say, to wheat) is very low, an additional kilogram of fertiliser will have, a large effect on yield. If on the other hand the soil is well endowed with nitrogen perhaps from last year's crop or from an inter-seasonal legume pasture, then an additional kilogram of nitrogen will have, only a small effect on yields. In the extreme, if levels of nitrogen are initially very high, any further provision may have a negative effect on yields. This is because, in dry conditions, water is a limiting factor and affects the productivity of nitrogen[1]. Diminishing marginal returns reflect a saturation effect. As a consequence, it would be a mistake to make a decision based

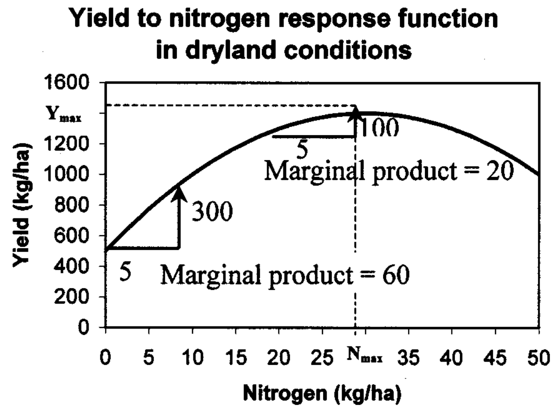

Figure 1. Crop yield in response to nitrogen application in dryland conditions[1].

on the average productivity of the nitrogen provided, where the yield is divided by the amount of nitrogen and the following *decision rule* is followed: if this ratio increases, continue providing nitrogen; if it decreases, reduce nitrogen. That is, the following decision criterion is not correct:

$$\text{maximise } Y/N \qquad (1)$$

Instead, a slightly better decision rule is to use the marginal value, or marginal productivity, of nitrogen, using the following formula:

$$\text{increase } N \text{ until } dY/dN = 0 \qquad (2)$$

This means: increase nitrogen provision until you have squeezed out all its yield improvement potential, until any further kilogram would only start decreasing yields and would therefore be wasted. In Figure 1, this corresponds to the amount of nitrogen N_{max} that produces the maximum yield Y_{max}. However, this strategy is economically optimal only if nitrogen comes at no cost at all. If it does have a cost, then it must be accounted for and compared to the benefits received from the market value of the nitrogen consuming crop. Figure 2 accounts for nitrogen costs. Decision rule 2 then leads to maximising the difference between the *cost* of nitrogen and the *benefits* from the consuming crop. When nitrogen is costly, it

[1] In wetter regions, where water is not a limiting factor, the yield curve would look different: it would flatten out at a maximum level without dipping back down. Note that the argument in this paper would not be affected by the form of the yield function, as long as a maximum yield could be defined.

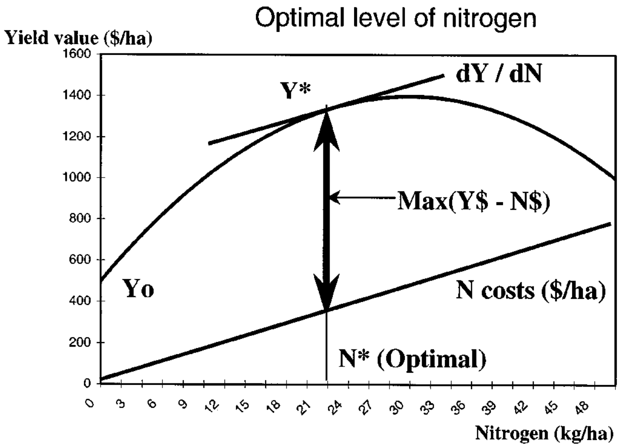

Figure 2. The economically optimal levels of nitrogen application and yield achievement.

is a mistake to strive for maximum yield Y_{max}, and therefore for the amount N_{max} that produces Y_{max}. The correct amount of nitrogen to be provided is N* which produces Y*, the economically optimal production plan. This plan gives simultaneously the optimal level of nitrogen to be provided and the optimal yield to be expected.

The previous result is based on the concept of marginal value applied to a given input (nitrogen) and a given output (e.g. wheat). The concept of opportunity cost expands the framework to include other possible inputs and other possible outputs. In our case, nitrogen can be provided through legumes or chemical fertilisers (alternative inputs), and the nitrogen can be provided, say, to wheat or to canola (alternative outputs). The reason why this is important is that, on the input side, providing nitrogen through a chemical fertiliser may be much cheaper, or more productive in terms of expected output yields, than relying on legumes. This will be the case if no legumes are well suited to the soils being farmed. On the output side, canola may fetch a much higher price than wheat, or yield a much higher gross margin (market price minus production costs), in which case the value of nitrogen to canola will be higher than its value to wheat.

The concept of opportunity cost also has much deeper implications. Suppose that to improve farm profits, a legume is replaced by a chemical nitrogen fertiliser. This will free up the land on which the legume would have been grown. Another crop, obviously a non-legume, will be grown instead. This in turn will disrupt the existing cropping rotation or crop sequence, perhaps forcing another crop (or pasture) to be planted in the following year than the one initially planned. Decreasing legumes on part of the land, or on a particular soil type, may also disrupt the whole-farm plan, for example if the legume crop was intended as a feed for livestock. The lack in feed would then have to be compensated by changing the land use pattern on *other* parts of the farm, perhaps by increasing legumes on *other* soil types. Alternatively, the farmer could buy on the market the missing difference. In both cases, farm profits will be directly affected, upwards or downwards, and that would immediately impact on the value of the initial legume (replaced by a chemical fertiliser) and on the fixed nitrogen it could supply. Valuation that accounts for full opportunity costs shows that gross margin analysis on a per hectare basis is not sufficient: it does not account for all the costs and benefits. Variations in whole-farm profit constitute the correct measure of value.

Having laid down the grounds for nitrogen valuation, how is it done in practice? We shall examine in turn the costing and the valuation.

3. IDENTIFYING THE COSTS OF NITROGEN FIXATION

Costing nitrogen fixation refers in the first place to the cost of growing the legumes that will provide the nitrogen. This is to be compared to the purchase of chemical fertilisers. In both cases, the costing is not necessarily straightforward. Even for chemical fertilisers, Baldock [1] shows that the "real" cost of nitrogen must account for:

- the N content of the fertiliser (%);
- potential losses from volatilisation, leaching, denitrification, and removal in grain;
- cost of lime to neutralise acidity caused by fertiliser;
- cost of transport, application and spreading;
- the value of P and other nutrients in compound fertilisers.

In addition, given that losses in volatilisation, leaching, and denitrification take time, by including or excluding them one defines:

- a short term cost of N (typically over one growing season);
- a long term cost of N (typically, over a whole cropping rotation).

For nitrogen fixed through legumes, the real cost may as above include the cost of lime to neutralise acidity from nitrogen fixation (as is the case with lupins in Western Australia), but will now be defined, as in [2], by the gross margin forgone of the *most profitable* non-legume alternative that *could* have been grown instead of the legume, minus:

- the gross margin of the legume crop;
- the return from disease break effects;
- the return from weed control effects.

These represent the benefits other than nitrogen fixation obtained by the legumes (summarised as the "yield boost" effect below). The gross margin of the *best* (most profitable) non-legume alternative constitutes the *opportunity cost* of growing the legume. The actual cost of nitrogen is thus defined by this opportunity cost net of the benefits other than nitrogen provided by the legume. If these are greater than the cost of forgoing the non-legume, then the true cost of providing fixed nitrogen is negative. If they are smaller, then the true cost is positive; that is, it is a real cost.

This definition of the cost of nitrogen fixation shows why it strongly depends not only on the legume used to provide it, but also on the crop (or pasture) that the legume displaces. Table I [2] demonstrates this dependence for a farming region in New South Wales, Australia. The cost of fixed nitrogen in this case is (for the following crop) much higher when obtained through lupins (*L. angustifolius*) than when obtained through field peas (*Pisum sativum*). This is because the economic cost of lupins compared to the alternative crop ($150/ha for canola and $112/ha for wheat) is much higher than that of field peas (resp. $61 and $23). The amounts of nitrogen fixed on average in the region by each legume (lupins: 38 kg/ha, peas: 24 kg/ha) play a lesser role: 40% of the difference compared to 60% for differences in opportunity costs. At the same time, fixed nitrogen costs are higher when a legume replaces canola than when it replaces wheat. This is because the net returns from canola are higher ($294/ha) than those from wheat ($256/ha)[2]. The same results hold for the longer term effects, when nitrogen is left in the soil after the following crop.

4. IDENTIFYING THE VALUE OF NITROGEN FIXATION

The value of fixed nitrogen encompasses the net effect of the cost of provision, as detailed above, and its benefits to the following crop. Thus, given the data of the previous section, fixed nitrogen will be worth more if it is used by a following canola crop than by wheat, since the net returns from canola ($294/ha) are higher than for wheat ($256/ha). The benefits, from an economic point of view, are measured by the amount of chemical fertiliser that will not need to be applied; that is, by the (negative) opportunity cost. However, fixed nitrogen is provided through a legume crop or pasture which provides other benefits than just fixed nitrogen. These include, usually over more than one year:

- long term slow-release of fixed nitrogen into the soil pool;
- disease break effect;
- weed control effect (especially legume pastures);
- soil structure effect;
- root structure effect.

It is convenient to summarise these effects by the term "yield boost effect", because, from an economic point of view, they translate into a higher yield potential for N-consuming crops in the following years[3]. The value of nitrogen-fixing legumes is then defined, for the following years where these effects are not insignificant, as the sum:

$$\begin{aligned}\text{Value of legumes} &= \text{Value of N fixed}\\ &+ \text{Value of “yield boost effects”}\\ &\text{to following crops.}\end{aligned} \tag{3}$$

The problem is, *how do we disentangle the two components of the value of legumes, so as to isolate the value of fixed nitrogen*?

The value of N fixed, in terms of its benefits to following crops, is defined as the amount of chemical nitrogen fertiliser saved in subsequent years, and mostly in the following year, *such that the expected yield remains the same*. That is, it is that part of fixed nitrogen that is directly available to following crops and can be replaced with chemical fertiliser[4]. Equation (3) then becomes:

Table I. Costs of fixed nitrogen in the South-West slopes region of NSW (Source: [2]).

Source: Brennan & Evans	Replacing canola		Replacing wheat	
Costs in $/kg N	Lupins	Peas	Lupins	Peas
Following crop	$4.01	$2.59	$3.00	$0.99
Longer term	$1.98	$1.35	$1.49	$0.53

[2] These net returns allow for disease break and weed control benefits, which exist for canola ($124/ha) but not for wheat in the region. The gross margins without these benefits are in fact reversed: $256/ha for wheat and only $169/ha for canola.

[3] This is an approximation, however, as the yield boost component may also include some nitrogen fixation effect.

[4] In this discussion, it is assumed that chemical fertilisers are always a possible option, an assumption that is true in most parts of the world today. If chemical fertilisers were not available, or totally beyond reach for subsistence farmers, then it is important to note that the value of N-fixed would *only* be measured in terms of the "yield boost" effects.

$$\text{Value of legumes} = \text{Savings in N fertiliser} + \text{Value of “yield boost effects” to following crops.} \quad (4)$$

The savings in fertiliser must be determined experimentally and through the use of a fertiliser production function, as was earlier illustrated in Figure 1. When nitrogen and yield are measured in physical units, one obtains the physical production function. However, a physical production function is not sufficient for decision making, since it does not account for costs and benefits. The actual savings in nitrogen fertiliser will depend on the changes in the economically optimal amounts of fertiliser that correspond to the economically optimal yield levels, as were defined in Figure 2 above.

To determine the savings in nitrogen fertiliser allowed by legumes, both the N fixation and the yield boost effects must be considered. The total effect in terms, firstly, of the physical production function is shown in Figure 3. Yields as a function of applied fertiliser nitrogen when no other nitrogen is directly available from the soil are shown as curve $Y_0 - Y_{max}$. If a legume was grown in the preceding season and an amount N'_0 is directly available from the soil, the yield-fertiliser response curve becomes $Y_0' - Y'_{max}$. The shift upwards from curve Y to curve Y' represents the “yield boost” effects. The specific effect attributable to N fixation is the reduction in yield response to nitrogen fertiliser application: $Y'_{max} - Y_0'$ instead of $Y_{max} - Y_0$. This is because the curve to the left of Y_0' (which should only have been a dotted line in the graph) is irrelevant: there already is, by assumption, a quantity N_0' of nitrogen available to the crop before any fertiliser is applied. Because of the law of diminishing marginal returns, the extra productivity of fertiliser application is reduced as the initial available nitrogen in the soil increases.

As stated in the previous paragraph, the actual level of production will not be at Y_{max} or at Y'_{max} and that of fertiliser application will not be at the corresponding N_{max}. Instead, the costs of fertiliser will be accounted for and set against the benefits from any increase in yields. This is shown in Figure 4. It is basically the same as Figure 3, except that now the vertical axis measures, in dollar terms, both the costs of N fertiliser and the benefits from increased yields. Following the principle of marginal valuation (see first section above), and the fundamental law of economic optimisation, nitrogen application will be increased up to the point where any further increase in the value of production is offset by the costs of fertiliser application. Mathematically, the derivative of the production function will need to equal the slope of the (linear) cost curve. This defines the points Y* and Y*' which represent the optimal level of production. This is also equivalent to maximising the difference between the yield benefits and the fertiliser costs (represented by the lower thick double-ended line). The corresponding level of nitrogen fertiliser is N*. Since fertilisers are costly, one shall always have $N^* < N_{max}$ (compare Figs. 3 and 4). The savings in N fertiliser from legume fixation are given by the difference $(N'_0 - N_0)$, and:

$$\text{Value of N fixation} = (N'_0 - N_0) \times \text{price of N.} \quad (5)$$

As well:

$$\text{Value of yield boost effects} = Y^{*\prime} - Y^*. \quad (6)$$

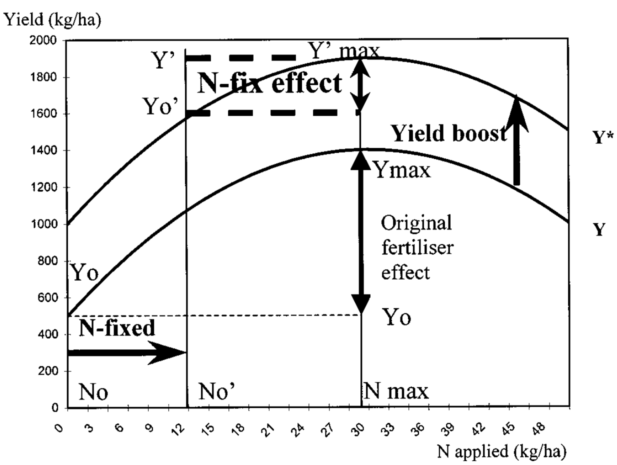

Figure 3. Identifying the impact of nitrogen-fixation on the fertiliser effect.

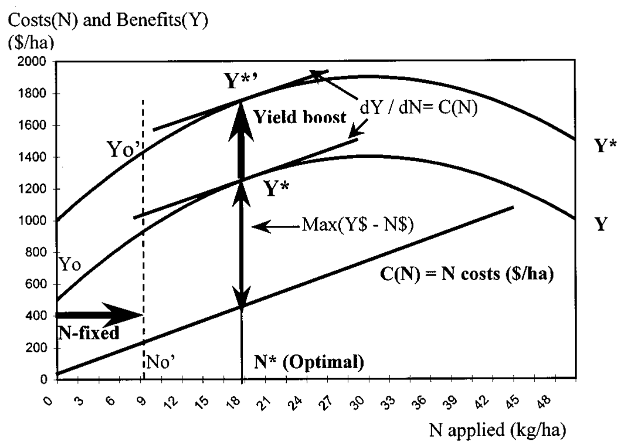

Figure 4. Identifying optimal fertiliser application and optimal yields.

Figure 5 shows what would happen if the costs of nitrogen fertilisers were so high that the optimal level of application would be zero ($N^* = N_0'$). This may represent certain situations in less developed rural economies. In this case, we are still assuming a given amount of nitrogen available in the soil (N_0'), but the value of nitrogen fixed by legumes will be entirely due to yield boost effects, represented by ($Y^{*\prime} - Y^*$); fertiliser savings will not enter the calculation. This is a point worth noting. Even when nitrogen fixation does not save on fertilisers, it is not true that legumes must not be grown. From a farm management perspective, this is an indication that the legumes as a whole are more important than nitrogen fixation. However, the specific value of nitrogen fixation remains important for research and development purposes.

We have thus defined a procedure that allows us to disentangle the two components of the value of legumes and to isolate the value of nitrogen fixation, at least in principle. In practice, however, this is not sufficient. Recalling Section 1 above, value is to be defined in reference to whole farm profits, not to any crop-specific gross margin. This is because, as gross margins change across farm enterprises, farmers are free to change their land use pattern. They will increase the area of enterprises that yield higher returns, thus reducing the areas of the remaining enterprises. These adjustments are a direct response to the changes in farm profits caused by a change in any specific enterprise. If numbers of livestock change, this will affect the relative areas of crops and pastures, and of fodder-providing to non-fodder providing crops.

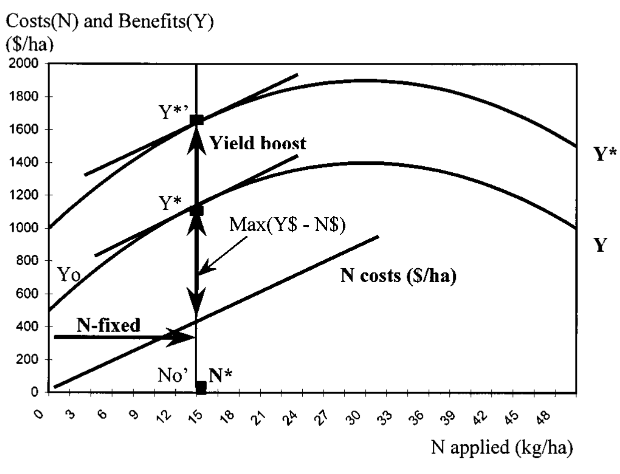

Figure 5. When the value of nitrogen is only in yield boost effects.

Consequently, the value of nitrogen fixation cannot be computed directly from changes in any specific crop yields, even when these changes are a function of legume benefits. Instead, the value of nitrogen fixation needs to be computed from changes in the profit function brought about by legume effects. Because such changes involve the whole farm structure, some way of representing these structural changes is needed. This is possible through the use of whole farm models.

5. COMPUTING THE VALUE OF NITROGEN FIXATION: THE NEED FOR WHOLE-FARM MODELS

Whole farm models have been around for quite some time, at least since the 1960s, when linear programming and computers began to shoulder each other. Linear programming is a mathematical technique, invented by George Dantzig in 1951 [3], which considers an activity system (such as a farm) with an objective function (profit maximisation) and a set of resource constraints (availability of land, labour, machinery, and finance). The activity system is described in a modular fashion, meaning that every activity is defined in terms of basic units (e.g. numbers of hectares), each yielding specific contributions to profit. For instance, a hectare of canola may yield a higher contribution to farm profit than a hectare of wheat, but it needs soil types that are scarcer or more costly to maintain in good condition. The linear programming algorithm then solves the problem by finding the number of basic units (e.g. hectares) of each activity that, given the available resources, will produce the highest possible whole-farm profit. Table II shows the fundamental structure.

When there are only two activities (canola and wheat) or two resources (land and labour), the linear programming problem can be solved graphically; but for a larger number of either, a computer program is needed. There are several commercially available, some of which can handle thousands of activities and resource constraints. However, knowledge of linear programming and having an efficient computer package is far from sufficient to model a farming system. A thorough understanding of the farming system itself is needed and in particular of the many interactions within it. Quite generally, there will be interactions between crop, pasture and livestock enterprises, between crops and pastures over time through sequential effects, and across the whole farm through use of common resources (land, labour, machinery). Even where there are different soil types, each with different production characteristics, decisions relating to one soil type will, through the use of common resources, impact production on all other soil types. Farming needs

Table II. Example of a linear programming matrix.

Unit coefficients	Activities: Wheat (1 ha)	Lupins (1 ha)	Pasture (1 ha)	Sheep (1 DSE)	Constraints
Soils (ha)	– 1	– 1	– 1	0	≤ 200 ha
Nitrogen (kg)	– 50	+ 20	+ 10	0	= 0 (no unused)
Labour (h)	– 20	– 15	– 5	– 5	≤ 4000 h
Feed /residues (kg)	+ 20	+ 40	+ 60	– 30	= 0 (no stocks)
Unit values	$300/ha	$160/ha	0	$60/dse	

LP algorithm maximises 300 W + 160 L + 60 S subject to the 4 constraints and the unit coefficient values.
DSE: Dry Sheep Equivalent.

a very systemic kind of analysis. Whole farm models grounded in linear programming allow for such interactions and for implementing a systemic approach.

In Australia, the MIDAS family of whole-farm models describe farming systems and their bio-economic interactions. Nitrogen fixation is a biological interaction that leads, through the changes seen above in fertiliser levels and through adjustments in legume and non-legume areas, to such bio-economic interactions. In effect, MIDAS has been used to compute the value of nitrogen fixation for a specific agricultural region in Western Australia. Before presenting the results, a brief description of MIDAS is necessary.

MIDAS stands for “Model of an Integrated Dryland Agricultural System” and describes a Mediterranean farming system in the so-called wheat-belt of south-west Western Australia [5, 6]. The specific version presented here describes one of the wheat-belt regions known as the eastern wheat-belt (EWB) – see map in Figure 6. It is situated in the drier parts of the wheat-belt, where long term rainfall averages 330 mm per year, with most falling during the winter and spring months (May–October). Farms in the area are typically very large (MIDAS assumes 2500 ha arable), single family owned, and highly mechanised. MIDAS is designed to maximise, not this year’s profits, but longer-term profits as consolidated over the whole length of rotations (3 to 5 years). It assumes, according to versions, 4 to 7 soil types, which are better described as “land management units”. They range from the lighter (sandy) to the heavier (clayey loam) soils. MIDAS describes in detail interactions between sheep enterprises (no other commercial livestock in the region), pasture and cropping activities [6]. Cropping and pasture activities are described embedded within rotations or crop sequences, accounting for the fact that each crop or pasture will behave differently

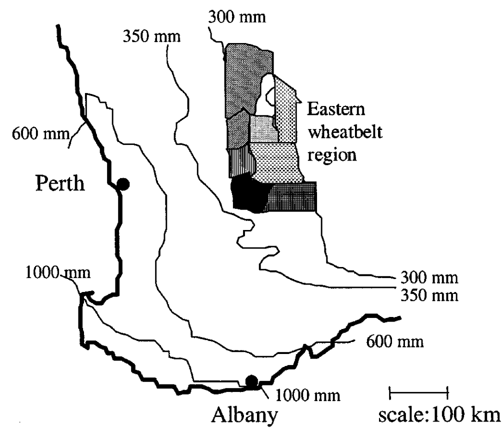

Figure 6. Map of south-west Western Australia and situation of the eastern wheatbelt.

depending on its position in the sequence. Of particular relevance to our purpose, the version of MIDAS used endows each crop with a specific (quadratic) nitrogen production function that is also specific to each soil type and each rotation. In other words, MIDAS has as many curves of the type shown in Figure 4 as there are soil types, rotations and crops[5]. MIDAS does not account for any long term dynamics, but describes a steady-state system in equilibrium. Although not very realistic as a descriptive assumption, it is very useful as an analytical tool. Pannell [8] offers a decade-long historical review of

[5] For this and other reasons (e.g. use of machinery), a special version of linear programming, mixed-integer programming, was used.

using the MIDAS model and draws some conclusions for whole-farm modelling.

With the help of a whole-farm MIDAS model, the value of nitrogen fixation was computed for the eastern wheatbelt farming system of Western Australia [7]. Several forms of nitrogen fertiliser, both simple and composite, were included as possible substitutes (e.g. urea, DAP, ammonium sulphate). The providing legumes included lupins, field peas and pastures. Lupins are a light soil legume while peas tend to be a heavier soil legume. Pasture legume content varies with soil type and position in the rotation. In this version of MIDAS, pasture legume content varies from 20% to 60%. Nitrogen consuming crops are cereals, mainly wheat, but also barley, oats and triticale. Canola was not yet a major crop at the time of this study [7], and neither was the protein content of wheat. Today, the value of nitrogen for wheat has increased due to the protein premium policy introduced by the Australian Wheat Board [10]. Nitrogen will not only increase wheat yields but also protein content, which is considered as a quality factor paid at a premium [11]. It would be interesting to analyse the differential impacts on wheat protein content of applied versus fixed nitrogen.

6. THE VALUE OF FIXED NITROGEN IN THE EASTERN WHEATBELT OF WESTERN AUSTRALIA

Using MIDAS and the computation principles described earlier, the value of fixed nitrogen was computed for a typical eastern wheatbelt farming system. The results are shown in Table III and in Figure 7. To obtain the value of nitrogen fixation, the benefits of legumes in terms of savings in nitrogen fertilisers were set to zero, and the corresponding farm profit was compared to that of the standard model. In other words, the value of nitrogen fixation for the whole farm was calculated as the profit with nitrogen fixation benefits minus the profit without these benefits. Forgoing these benefits reduced farm profits by 11%, not an insignificant number. However, the yield boost effects were larger and “weighed” 37% of farm profits instead of 11%. Higher fertiliser costs would have increased the (relative) value of nitrogen fixation, whereas higher prices for wheat and other cereals would have decreased it relative to that of yield boost effects. As for higher legume prices, they would have led to complex interactions which only a specific MIDAS analysis could have sorted out (such an analysis was not carried out in this study). However, the more interesting results follow.

From Table III it is apparent that adding the values of nitrogen fixation and yield boost effects, whether in absolute or in percentage terms, does not lead to the total value of legumes. This may come as a surprise, given equation (3) above. Note however that the total value of legumes is less than the sum of both its component values, a fact that is consistent with the law of diminishing marginal returns if, and only if, the value of one component depends on the level of the other, and vice versa. That this is the case tells us that the two forms of nitrogen do interact and the value of either one depends on the level of the other. This is consistent with Figures 3 to 5, but it does not tell us where these interactions come from. Figure 7 sets us on the right track.

Figure 7 provides information underlying the results of Table III. It shows that when the benefits from nitrogen fixation are removed from the whole-farm model, the farming system readjusts itself so as to minimise the negative impact this will have on farm profits. It does so by reducing the proportion of crops to pastures from 62% to 48%. Note that this cropping percentage is only one way of describing the underlying structural changes. Another description would have been the proportion of legume to non-legume crops, with pasture possibly lumped in with legumes[6]. Obviously, for representational simplicity, only one structural change may be shown at a time. However, in MIDAS as in reality, structural change is a multidimensional phenomenon. Is there any way to account for all such changes simultaneously?

Table IV provides the answer in terms of the values of the two forms of nitrogen. Focusing on nitrogen fixation, we see that at the whole farm level its value is higher when fertiliser substitutes are not available. In this study, it was roughly 4 times more valuable. This result accounts for both the marginal value and the structural change effects, the latter reflecting relative opportunity costs across the farm.

What is true for the whole farm is also true for parts of it, in particular for certain soil types. As Table V demonstrates, the value of nitrogen and legumes also depend on soil type. This information is of interest for guiding research and development programs, by highlighting on what soil types, given current economic conditions, nitrogen fixation will be most profitable to farmers. In the process, the specific legumes providing this form of nitrogen will also be identified. For example, Schilizzi and Kingwell [12] showed that for the same region of Australia, partly as a consequence of the value

[6] This lumping together with legumes could perhaps be made conditional on its legume content being above a certain threshold.

Table III. Values of legume benefit components in MIDAS for a 2500 ha farm (adapted from [7]).

Value of	$ value 2500 ha	$ value/ha	% max profit	% crop on farm
N-fix	$ 4700	$ 1.90	11%	48%
Y-boost	$ 15640	$ 6.25	37%	60%
Legumes	$18020	$7.20	43%	58%
Notes	L < N + Y	Profit = $ 18/ha	43 < 48	Reference 62%

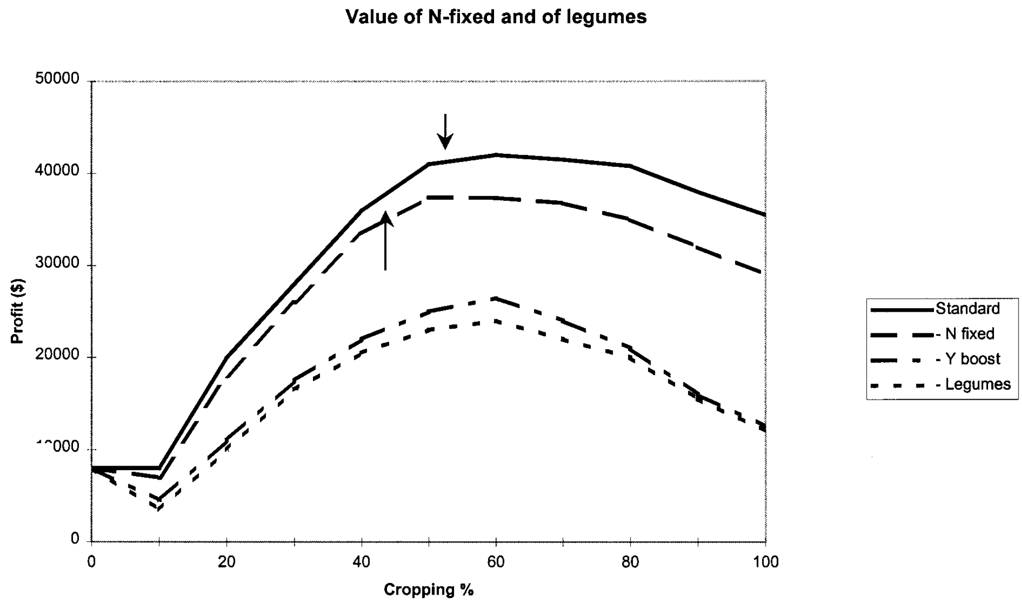

Figure 7. Value of nitrogen fixation in a whole-farm setting as the difference between the standard and the "minus N fixed" case, for the eastern wheatbelt of Western Australia (Merredin region).

of nitrogen fixation and yield boost effects, chick peas were a robust addition to farm profits. They were worth systematically including in rotation with cereals on specific soil types, identified in the study[7]. Because chick peas were still a new crop in the region, improving their nitrogen fixing and yield boost capacity was shown to be a worthwhile research and development goal.

Table V also shows that the effect of the interactions does not remain stable across soil types. For example, on good light soils, the (total) value of legumes was twice more valuable when fertilisers were available than when they were not, whereas on heavy soils the relationship was reversed: they were *less* valuable when fertilisers were available! Again, this seems to contradict the principle of diminishing marginal returns, but as was the case in Table II, we must suspect underlying structural changes in the farming system. What are they in this case?

Table VI provides the answer. Rotations are being changed in the optimal farm plan. When legume benefits are removed from good light soils, this induces the abandonment of lupins in the optimal rotation and their replacement by cereals. The cereal:cereal:lupin (CCL) rotation is replaced by a continuous cereal crop. Since lupins are partly used as animal feed, this will impact on the livestock enterprise: this reduction in available feed must be compensated with increased lupin purchases, wheat residues, or by reducing the number of sheep. When both legume benefits and availability of fertilisers are removed on good light soils, not only do optimal rotations change on this soil type, but also on poor light

[7] This study used a more sophisticated version of MIDAS, called MUDAS, which includes price and yield uncertainties, tactical adjustments to initial farm plans and farmer risk aversion (see also [4]). It is a stochastic version of MIDAS.

Table IV. Values of fixed nitrogen and fertilisers interact.

	Included	Excluded
N-fixed		
Value of fert-N ($)	12 640	24 610
N-fertiliser		
Value of fixed N ($)	4 700	16 670

Table V. Legume / fertiliser interactions on different soil types.

$ Values	Value of legumes		Value of N-Fert.	
Soil type	+ Fert.	– Fert.	+ Legum.	– Legum.
Poor light	310	0	310	0
Good light	9 640	4 890	7 090	2 340
Medium	3 630	3 081	4 850	4 302
Heavy	940	1 110	0	170

Table VI. Whole-farm rotational adjustments in response to nitrogen reductions on one soil type.

Legumes	+	+	–	–
N-Fertiliser	+	–	+	–
Profit ($)	**42120**	**35030**	**32470**	**30140**
Poor light	PPPC	PPPC	PPPC	CCL
Good light	***CCL***	CCL	***CCCC***	***PPPP***
Medium	CCL	CCL	CCL	CCL
Heavy	PPPC	PPPC	PPPC	PPPC/PPC

Legend: P = pasture; C = cereals; L = lupins.

and heavy soils. Cropping becomes unprofitable on good light soil and is replaced with continuous pasture. With this extra pasture it becomes profitable to replace pasture with lupins on poor light soil and some pasture with cereals on heavy soil. These cross-soil type changes demonstrate the importance of accounting for whole-farm effects. Not doing so would lead to erroneous over-estimates of the value of nitrogen.

7. CONCLUSIONS

Defining and computing the value of nitrogen fixation requires two basic ingredients: sound economics and a whole-farm systems approach. The economics are based on the principles of marginal valuation and opportunity cost which together help identify the optimal form and level of nitrogen to be provided. They help disentangle the value of fixed nitrogen from the total amount of nitrogen provided and from the value of the legumes that provide it. Legumes provide other benefits than nitrogen fixation that boost the potential yields of following crops. However, to actually compute these values, a whole-farm model is needed that includes soil types, rotations and resources common to several enterprises, such as land, machinery and finance. As for the concept of value itself, gross margins and budgeting techniques will not yield correct results as they exclude many opportunity costs and do not relate to the objective function the farmer is trying to maximise: farm profits. These profits are not necessarily annual: they can encompass several years, for example over a typical cropping sequence.

Within this framework, it is easy to understand why the value of nitrogen fixation cannot be defined in absolute terms but will always depend on how it fits into the farming system. It will depend in particular on soil type, on the cropping sequence, on the value of the legume and of the following N-consuming crop, and on the cost of fertilisers. In the examples considered in this paper, it turned out that the yield boost effects of legumes were worth more to farmers than their nitrogen fixation capacity. This was largely due to high wheat prices and low legume and fertiliser prices at the time of the study. The value of fixed nitrogen also depends on whole-farm aspects such as the relative distribution of soil types, the opportunity costs involved in replacing a non-legume crop by a legume, and the consequences of such replacement in terms of across the farm adjustments to rotations, land use and livestock management. Luckily, today's computers allow for efficient implementation of appropriate whole-farm modelling techniques.

These results also send a message to scientists and extension workers by highlighting, in a given region, where research and development efforts have to be targeted so as to maximise the returns of such efforts. Economics again! However, this does not mean that research must be dictated by profitability considerations alone. Prices, technology and agricultural policies tend to change unpredictably in the future. It is wiser to consider the economic value of nitrogen fixation in terms of its robustness to variable prices and production parameters, in particular those of legumes, N-consuming crops and fertilisers. In other words, a stochastic version of the analyses reported in this paper would be a better guide for research and development purposes[8]. Alternatively, a comprehensive sensitivity analysis of the parameters

[8] For example, the MUDAS model mentioned above would be better suited than any of the MIDAS models.

involved, possibly using Monte-Carlo techniques, could be done with similar benefits without the need for a stochastic model[9]. For nitrogen fixation, this does not appear to have been done yet.

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[9] See Pannell's [9] paper on strategies using sensitivity analysis in farming systems. Monte-Carlo techniques involve completing hundreds or thousands of runs with random parameter values then examining the statistical properties of model solutions.