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Methodological limitations in the evaluation of policies to reduce nitrate leaching from New Zealand agriculture

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The land-use optimisation framework, *NZFARM*, has been promoted as a tool that can be used to assess the economic and environmental impacts of policy on regional land use. This paper outlines how methodological limitations presently restrict its capacity to provide meaningful insight into the relative value of alternative land-use configurations. The model is calibrated using positive mathematical programming, which has been shown in the literature to result in models that yield arbitrary output outside of the calibrated baseline. There is a high likelihood that this is the case, as no validation appears to have been carried out. Significant model development will be required before *NZFARM* outputs can be used with any confidence to inform future policy development. We conclude with suggestions on how *NZFARM* and models of its kind can be further developed to improve their capacity for meaningful simulation.

Key words: calibration, land-use optimisation, nonpoint pollution, validation.

1. Introduction

The impact of nutrient leaching on water quality from intensive agricultural production throughout New Zealand is well known (Monaghan *et al.* 2007; Parliamentary Commissioner for the Environment 2012). Achieving future improvements in water quality through the formulation of appropriate regulatory responses has thus been a key focus of researchers and regulatory bodies. One example is the implementation of a trading scheme in the Lake Taupo catchment to reduce nitrate leaching from farms in this area (Greenhalgh and Selman 2012). There has also been extensive work undertaken that aims to estimate the cost of abatement accruing to different regulatory methods in different regions (e.g. Doole and Pannell 2012; Doole *et al.* 2013a).

NZFARM has been promoted as a tool that can 'help decision-makers assess the potential economic and environmental impacts of policy on regional land use' (Landcare Research 2013). The model has been developed

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for the Hurunui/Waiau and Manawatu catchments with the intention of covering additional catchments as data become available. It has been used to assess changes in land use, farm management and environmental outputs for future policy scenarios, such as caps on nitrogen and phosphorous loads and implementation of the New Zealand emissions trading system on the forestry and agriculture sectors.

This model has the potential to inform the development of plans and policies by regional councils throughout New Zealand and by central government. For example, the New Zealand Ministry for Primary Industries has recently published a technical paper entitled, 'Evaluation of the impact of different policy options for managing to water quality limits' (Daigneault *et al*. 2012). This work is extensive in its coverage, reviewing the impact and costs of alternative regulatory instruments in three catchments. The analysis for two of these catchments was performed using *NZFARM*.

We fully support research into the impact of different policy options for managing water quality. The research described in Daigneault *et al*. (2012) contributes greatly to our understanding of these effects. Based on our analysis and knowledge of the literature, we support many of the generalised findings that are summarised on pages xvii to xix. In particular, we note the findings around mitigation costs, catchment-wide cap-and-trade programs and the importance of considering the distributional impacts of alternative allocation schemes. Nevertheless, we have a hypothesis that *NZFARM* is seriously limited in its current capacity to meaningfully inform environmental policy, given that inadequate calibration and validation restrict its capacity to adequately predict land use outside of the baseline situation. Additionally, these limitations extend more generally to land-use optimisation models used to inform policy.

Daigneault *et al*. (2012) list a number of key limitations with their analysis in the executive summary of their report. However, our concern is that important deficiencies associated with the use of positive mathematical programming (PMP) (Howitt 1995; Johansson *et al*. 2007) for calibration (adjustment of the structure and inputs within a model until it approximates a given baseline) and a lack of model validation (testing the capacity of the model to predict meaningful outcomes outside of a reported baseline) are not identified. PMP has been shown in the literature to result in models performing illogically, and potentially implausibly, outside of the calibrated baseline (Heckelei 2002; Heckelei and Wolff 2003). The probability that this has occurred is higher in this case since no validation appears to have been carried out. These factors are important to discuss, as inappropriate modelling has significant potential to misinform policy development, and it is difficult to manipulate policies after their introduction, particularly due to legal constraints. This discussion is also very timely for two reasons. First, *NZFARM* is the primary tool available to assess the relative costs of alternative environmental policies in New Zealand. Second, there is currently a strong legislative and social focus on improving water quality in this nation (Marsh 2012).

We explain below how the use of PMP produces arbitrary results in modelling future outcomes and provide specific examples of such results. We contend that significant development will be required before *NZFARM* outputs can be used with any certainty to inform future policy development. We conclude with a summary, including practical suggestions for the future development of *NZFARM* and other catchment-level modelling approaches that can enhance their value for informing the development of effective environmental policies.

2. Calibration of *NZFARM*

The construction of optimisation models that highlight how land use should change to achieve environmental targets – such as reduced nitrogen leaching – at least cost is now a mature field of applied research within the discipline of environmental economics (Howitt 1995; Heckelei and Wolff 2003; Nordblom *et al*. 2006, 2010). This practice is referred to as 'land-use optimisation' hereafter.

A simple example of land-use optimisation can be defined as follows. The goal of such a model is typically to identify the number of hectares to allocate between given land uses in a single year to achieve given environmental outcomes. In this pedagogical example, let us assume that we wish to identify the number of hectares to allocate between dairy farming (H^D) and sheep farming (H^S) in a catchment with a total size of a ha. These variables H^D and H^S are the decision variables in the problem that are determined by a mathematical (optimisation) algorithm (Vanderbei 2007). Suppose that dairy and sheep farming leach n^D and n^S kg N per ha per year, respectively, while total nitrate leaching in the catchment is defined as N. Also, assume that dairy and sheep farming earn profit of p^D and p^S dollars per ha, respectively. In New Zealand, these profit (p) values are typically derived from farm accounts or farm simulation models, such as FARMAX (Bryant *et al*. 2010), while the leaching (n) values are typically derived from nutrient-cycling models, such as OVERSEER (Wheeler *et al*. 2003).

A typical land-use optimisation problem (*P1*) is then defined as the maximisation of total profit (TP):

$$\mathrm{TP} = p^D H^D + p^S H^S, \tag{1}$$

subject to the equations:

$$a = H^D + H^S, \text{and} \tag{2}$$

$$N = n^D H^D + n^S H^S. \tag{3}$$

Equation 1 is the objective function, the expression we seek to maximise in the optimisation problem. It defines total profit as a linear function of land use. Equation 2 requires that the sum of dairy and sheep land must equal the total size of the catchment. Equation 3 determines the total level of nitrogen leaching (N) arising from land-use allocation.

Subsequent simulations generally will involve restrictions being placed on N, for which the model will identify how land use should change to attain different leaching goals, while maximising profit. For example, a 10 per cent restriction on nitrate leaching would be investigated through performing a second simulation with an additional equation included:

$$\bar{N} \geq N, \tag{4}$$

where the total nitrogen limit ($\bar{N}$) is computed through $\bar{N} = N^0 \times (1 - 0 \cdot 1) = N^0 \times 0 \cdot 9$ and N^0 is the level of N identified for the catchment in the optimal solution obtained in the baseline model (that involving just equations 1–3).

The optimal levels of land use (H^D and H^S) determined in this type of model will seldom, if ever, equal observed land use when the model is run without prior calibration. Rather, extreme divergences from the observed baseline will typically occur, as the optimal allocation of land from one type to another will be based on the relative value of each land use. Each equation in *P1* is linear; this classifies *P1* as a linear-programming problem (Vanderbei 2007). Accordingly, all land will be allocated to the most-profitable land use upon optimisation. For example, if the profitability of dairy farming is greater than the profitability of sheep farming ($p^D > p^S$) in *P1*, even by a single cent, then all land will be allocated to dairy farming. Of course, such overspecialisation is seldom observed in agriculture and reflects the inability of the model to adequately describe reality.

Attempting to achieve an accurate description of current land-use patterns (i.e. the baseline land-use allocation) is the primary difficulty encountered in land-use optimisation models, alongside the identification of reliable input data. Accordingly, various methods have been developed for overcoming this limitation. One may restrict land use through the addition of equations that either fix the land area that a given land use must cover or provide lower and upper bounds for this area (Hazell and Norton 1986). This coarse approach is easily implemented, but limits the degree to which one can study how land use could or should change in response to different policy mechanisms or environmental targets.

Another option to prevent overspecialisation is to introduce nonlinearities in the objective function to manipulate the relative value of each land use. In the context of the pedagogical example (*P1*) introduced above, calibration functions can be defined for the dairy and sheep enterprises as $c^D(H^D)$ and $c^S(H^S)$, respectively. The profit relationship, defined in equation 1, is then restated as:

$$\text{TP} = \left[p^D H^D + c^D(D^D)\right] + \left[p^S H^S + c^S(H^S)\right], \tag{5}$$

where the first term in square brackets describes the total profitability of dairy farming and the second term describes the total profitability of sheep farming.

Equation 5 states that the profitability of each land use now consists of its standard profit value (p), which is estimated from farm accounts or farm modelling, and a calibration function (c).

These nonlinear calibration functions can represent market or farm-level factors, such as endogenous prices or the incorporation of risk preferences (Meister *et al.* 1978; Hazell and Norton 1986). However, significant calibration of these relationships is still required if the model output is to approximate the reported baseline (Howitt 1995). The most popular alternative to these methods is positive mathematical programming (PMP). Howitt (1995) shows that a linear model can be calibrated to a baseline land-use allocation exactly, provided that the calibration terms are nonlinear and satisfy several other general conditions. The inclusion of these nonlinear functions is typically justified based on the intuition that these terms represent all of those factors not represented in the naive model *P1*. These omitted factors represented by the calibration function are generally broadly defined, consisting of aggregation bias, errors in input data and particular input–output relationships, such as decreases in yield as land use expands due to the employment of less-suitable soil types (Howitt 1995) or costs increasing with higher stocking rates on dairy farms (Doole and Pannell 2011).

The methods used within PMP to achieve exact calibration generally involve the estimation of appropriate calibration functions using data computed from a version of the linear model (*P1* in the pedagogical example) in which observed land use is constrained to equal its baseline level (Howitt 1995; Johansson *et al.* 2007). This technique has been broadly applied since its inception (e.g. Arfini and Paris 1995; Kanellopoulos *et al.* 2010; Doole and Pannell 2012). Its popularity can perhaps be explained by its capacity to yield exact calibration, simplicity, flexibility, the lack of robust and convenient alternatives, its ability to generate smooth response surfaces, and the significance of the problem posed by overspecialisation.

The *NZFARM* model, as discussed in Daigneault *et al.* (2012), is calibrated using a variant of PMP that requires the estimation of nonlinear calibration functions for alternative land uses in the model. These calibration functions are technically specified as constant elasticity of transformation (CET) functions. CET functions have been broadly applied in both general equilibrium (Diao *et al.* 1998) and environmental policy modelling (Johansson *et al.* 2007). The general CET approach, consistent with other types of PMP, achieves calibration to baseline land-use levels through manipulating the value of land uses away from their estimated profit levels (e.g. p^D and p^S in *P1*). As a PMP method of calibration, the technique applied to estimate CET functions within *NZFARM* has received substantial criticism over the last decade. The major concerns are as follows:

1. There is an infinite number of sets of calibration function parameters that can generate the observed baseline land use (Heckelei and Britz 2000, 2005; Heckelei 2002; Heckelei and Wolff 2003; Heckelei *et al.* 2012). This

problem exists as long as the number of calibration function parameters is higher than the number of observations.

2. Calibration does not use any information on how the relative value of land uses change as land-use allocation moves away from the observed baseline (Heckelei and Britz 2000, 2005; Heckelei 2002). Each one of the infinite sets of calibration function parameters – from which one is arbitrarily selected to calibrate the model to baseline data – yields a different policy response from the calibrated model. Thus, the way in which the model performs outside of the calibrated scenario is completely unpredictable (Heckelei 2002).
3. The theoretical basis of PMP is, 'weak or at least not apparent' (Heckelei and Wolff 2003, p. 28).
4. The relative value of alternative land-use activities is altered through the introduction of calibration functions. This complicates the interpretation of the estimated profitability levels used as initial inputs (i.e. p^D and p^S in *P1*).
5. Functional forms used for calibration functions in PMP implementations, such as the CET functions used in *NZFARM*, are generally ad hoc and difficult to justify based on the stylised facts of agricultural economics (Heckelei and Wolff 2003; Heckelei *et al*. 2012). This is generally evident since a small number of functions are used to replace what would ideally be a set of detailed model equations describing the individual determinants of the relationship between farm profit and nitrate leaching over a broad number of farm types.

In summary, the PMP approach assumes that the baseline land-use configuration is optimal, and can bias model output when different policy scenarios are simulated through penalising deviations from this baseline in an arbitrary way.

3. Examples of arbitrary results from *NZFARM*

The *NZFARM* modelling conducted in Daigneault *et al*. (2012) contains several results that strongly suggest that these limitations are evident in *NZFARM*. Examples are illustrative. Table 31 in their report records that the cost of a 53 per cent and 61 per cent decrease in N and P, respectively, in the Manawatu catchment is around 17 per cent of net revenue. This cost is very low considering the enormous land change that is evident in the optimal solution (Figure 22). This land-use change involves the following:

1. An additional 128,362 ha of the Tararua Hills area is now allocated to non-productive uses. This includes the loss of more than 100,000 ha of productive sheep and beef activity.
2. Replacement of more than 25,000 ha of dairy farming on the Tararua Flats by a mixture of beef and sheep farming, forest, deer farming, scrub and fallow.

3. Around 55,000 ha of land is taken away from productive uses and allocated to scrub and fallow on the Manawatu Hills.
4. Around 30,000 ha of dairy farming on the Manawatu Flats is replaced by a mixture of sheep and beef farming, deer farming, forest and scrub.

These results are surprising since they are inconsistent with general expectations regarding the relative value of alternative land uses in New Zealand. For example, point #1 highlights that all agriculture on the Tararua Hills should be replaced by a fallow activity that earns no income. Moreover, point #2 highlights that highly productive dairy land with a high opportunity cost on the Tararua Flats is partly replaced by unproductive scrub land. This inconsistency arises because the relative value of land uses has been manipulated through the calibration process to ensure that the observed land allocation in the baseline has been observed.

Such results are not evident for the Hurunui–Waiau catchment in the Daigneault *et al.* (2012) report, as land-use allocation effects are dominated by the introduction of the Waitohi irrigation scheme. Nevertheless, the effects of calibration are evident in other studies of the Hurunui–Waiau catchment performed using the *NZFARM* model. Samarasinghe *et al.* (2011) used *NZFARM* to estimate how optimal land use changes if the aim was to reduce nitrogen and phosphorus by 30 per cent within this catchment, with nutrient loads measured using OVERSEER. These authors highlight that net revenue falls by only 6 per cent. This is surprising given that dairy area is halved and replaced mainly by forest and some arable land, and a third of sheep and beef land is replaced by forest (Figure 4).

Additionally, Samarasinghe *et al.* (2012) used *NZFARM* to estimate how land use would need to change to achieve 15 and 30 per cent reductions in nitrogen across the Hurunui–Waiau catchment. These goals are estimated to cost around 1 and 6 per cent of net revenue, respectively. These costs appear inconsistent with the significant land-use change required to achieve these reductions. For the 15 per cent nitrate leaching goal, around 25,000 ha of dairy and sheep and beef land is replaced by approximately 21,000 ha of forest, 2,000 ha of arable land and 1,000 ha of fallow (Figure 5). For the 30 per cent nitrate leaching goal, around 48,000 ha of dairy and sheep and beef land is replaced by approximately 37,000 ha of forestry, 9,000 ha of arable land and 2,000 ha of fallow (Figure 5). Like in the Manawatu catchment, these results appear inconsistent with expectations regarding the relative value of New Zealand land uses. Net revenue has fallen by a minimal amount with respect to the size of the nutrient goals obtained, though it is achieved with marked enterprise change, with milk production decreasing by 30 and 70 per cent, respectively, with a 15 and 30 per cent reduction in N leaching.

Our experience is that such counterintuitive results arising from a land-use optimisation model indicate problems with calibration. Our concern is greater in this particular case, as no validation appears to have been performed that tests the capacity of the model to predict outcomes outside of the baseline land-use allocation. Moreover, the simulations involve significant extrapolation from the simulated baseline, which raises further doubt regarding how meaningful the calibration functions are in this context.

4. Validation of *NZFARM*

Doole and Pannell (2013), in a recent article entitled 'A process for the development and application of simulation models in applied economics', provide a discussion of model validation as a key step in economic modelling. They state (p. 94):

> *Establishing the validity of a model is critical to maintain the relevance of a modelling exercise (Landry et al. 1983)... Three necessary, but not sufficient, conditions for effective model validation are (Naylor and Finger 1967):*
>
> 1. *Model structure to be consistent with the stylised facts of important system processes.*
> 2. *Input data to be consistent with expected or reported values.*
> 3. *Output to be consistent with expected or reported values for a range of scenarios.*

In our view, the *NZFARM* modelling in Daigneault *et al*. (2012) does not meet any of these conditions. Ideally, a catchment model should describe in detail the important processes that drive the relationship between production, profit and environmental processes (Heckelei 2002). However, this is seldom achieved at the catchment level due to time and data constraints. Thus, point #1 is not satisfied as model structures seldom, if ever, contain a direct description of the important processes involved. This introduces a predicament – and the core motivation for calibration – as practitioners must try to meaningfully approximate these processes in a concise manner for multiple enterprises.

Input data in a calibrated catchment model consist of accounting data, environmental data and that used to achieve calibration. *NZFARM* contains a rich description of pertinent accounting and environmental data (Daigneault *et al*. 2012). However, their impact on model output is not clear, as their relative influence is biased by the inclusion of the nonlinear calibration functions. For example, in Section 3 it is identified how *NZFARM* shows that it is cost-effective to replace productive agriculture with fallow in a broad range of circumstances. This shows that even though productive agriculture earns a nonzero profit, its relative value has been manipulated in such a way that the model produces counterintuitive results. Moreover, the calibration functions are not computed in a meaningful way; rather, the estimation process used in PMP is ad hoc and arbitrary (Section 2). These factors highlight that point #2 above is not satisfied either.

There also appears to be no validation of the model in terms of its capacity to predict outside of the calibrated scenario. This highlights that point #3 above is not fulfilled also. Meaningful output validation is necessary to provide confidence in the model to extrapolate away from sample data (McCarl and Apland 1986; Howitt 1995). This is particularly important given the concerns raised above regarding the potential limitations of PMP (Section 2) and because time series data are not used to estimate the calibration functions in *NZFARM*.

5. Summary and recommendations

Research indicates that the use of PMP for the calibration of land-use optimisation models, as done in *NZFARM*, leads to biased and arbitrary policy assessment. This is demonstrated by a number of *NZFARM* results that are strongly counterintuitive. PMP calibration functions that are statistically valid can be estimated using regression techniques – such as generalised maximum entropy methods (Golan *et al.* 1996; Heckelei and Wolff 2003) – that provide robust results in the presence of small samples and allow the use of prior information (Heckelei 2002). However, the critical limitation of PMP remains the inability of heuristic calibration functions to meaningfully represent the response of decision-makers to alternative policy settings. Additionally, Heckelei and Wolff (2003, p. 24) highlight that the theoretical basis of this approach is, 'weak or at least not apparent'. Accordingly, it is strongly apparent that PMP should not be employed within *NZFARM* or land-use optimisation models, in general.

Nevertheless, several pragmatic strategies can be used to enhance the value of land-use optimisation models for informing the development of effective environmental policies:

1. Land-use allocation can be restrained to remain within the set of historical land-use allocations (McCarl 1982) or inside a set of land-use allocations that has been robustly generated using econometric techniques based on historical data (Chen and Onal 2012).
2. Land-use choice on a given parcel of land can be restricted based on the characteristics of this parcel and common sense. For example, a hectare of prime dairy land could only be allocated to less-intensive dairy farming, cropping or lamb fattening, but not to forestry or fallow. Doole *et al.* (2013b) present an example of this method in an application concerning the mitigation of phosphorus and sediment in the Avon Richardson and Avoca catchments in Victoria, Australia. This approach is used in Daigneault *et al.* (2012) (see, for example, page 17–18), but available land uses seem to be very broadly defined for each parcel of land (see Section 3).
3. Output validation would ideally involve model output being compared with real data for scenarios outside of the calibrated situation (e.g. Heckelei and Britz 2000; Doole *et al.* 2013c). For example, the model

could be calibrated to data for a single year and then tested to see if it adequately replicates the data for another year or years. This validation would provide some evidence that the estimated calibration functions are meaningful and effective.

4. Independent verification of the model, particularly through international peer review, may also provide greater confidence in the capacity of the model to provide quality predictions outside of the calibrated baseline.

The adoption of these practices is reasonably straightforward and has significant potential to provide greater realism in predicting the effects of alternative environmental policies on future land use.

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The authors would like to draw the readers' attention to a correction in the above article:

Following clarification provided by the modellers who developed *NZFARM*, the numbered list provided in Section 3 of the article identifying the model's estimated land use change for the Manawatu catchment should read:

1. An additional 128,362 ha of the Tararua Hills area is now allocated to non-productive uses. This includes the loss of more than 100,000 ha of productive sheep and beef activity.
2. Replacement of more than 25,000 ha of dairy farming on the Tararua Flats by a mixture of sheep and beef farming, forest, deer farming, scrub and fallow.
3. Approximately 55,000 ha of land is taken away from productive uses and allocated to scrub and fallow on the Manawatu Hills.
4. Approximately 30,000 ha of dairy farming on the Manawatu Flats is replaced by a mixture of sheep and beef farming, deer farming, forest, and scrub.

The authors apologise for any confusion that may have been caused by this correction.

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