Linking models for land use analysis: experiences from the SENSOR project

Jansson T.[1]*, Bakker M.M.*[2]*, Boitier B.*[3]*, Fougeyrollas A.*[3]*,*
Helming J.[1]*, van Meijl H.*[1] *and Verkerk P.J.*[4]

[1] LEI, Wageningen UR, the Hague, the Netherlands.
[2] Land dynamics department, Wageningen University, the Netherlands
[3] ERASME laboratory, Ecole Centrale Paris, France
[4] European Forest Institute, Joensuu, Finland

Abstract— **In order to quantify the effects of a comprehensive set of policies on land use, interaction between sectors needs to be accounted for, while maintaining a high level of detail for each sector. This calls for a combination of *sector specific* and *sector wide* models. This paper describes such a modelling system, with emphasis on the linking of the models to a coherent system. Five sectors of significant importance for land use are modelled individually: Forestry, agriculture, urban land use, transport infrastructure, and tourism. All models are connected as sub-modules to an economy-wide partial econometric model. In addition, a land cover model is used to disaggregate land use down to 1km grid resolution.**

The linking of such a diverse set of models in a consistent way poses conceptual as well as practical issues. The conceptual issues concern questions such as which items of the models to link, how to obtain a stable joint baseline scenario, and how to obtain a joint equilibrium solution for all models simultaneously in simulation. Practical issues concern the actual implementation of the conceptually sound linkages and provision of a workable technical solution.

The linked system allows us to introduce a shock in either of the models, and the set of results will provide a joint solution for all sectors modelled in SENSOR. In this manner, the models take a complex policy scenario as argument and compute a comprehensive set of variables involving all five land use sectors on regional level, which in turn forms a basis for distilling out the impact on sustainability in the form of indicators. Without the extensive automation and technical linkages, it would not have been possible to obtain a joint equilibrium, or it would have required exorbitant amounts of working time.

Keywords— **Model linking, sustainable land use, cross sector modelling, iterative recalibration.**

I. INTRODUCTION

The linked system of models described in this paper was called for by the needs for quantitative analyses within the SENSOR project[1]. SENSOR applies a cross-sector approach to land use, acknowledging that different sectors of the economy interact via shared resources, of which land is of most interest in SENSOR. Although a cross-sector approach enables capturing important interactions between sectors—and thus analysing important topics—it brings modellers to a classical dilemma: a model with great scope is desired to include all sectors of interest, but such a model can pay less attention to the details of each sector.

Due to the trade-off between scope and detail, models tend to specialise in either one. In SENSOR, we attempt to resolve that dilemma by using a combination of models. For each of the sectors of interest, one specialised sector model is linked to a macro model spanning all sectors. In that way, the advantages of detailed sector models can be exploited, and at the same time the interactions between the sectors are captured by the aggregated model[2]. For example: The agricultural sector model in SENSOR is detailed concerning agriculture, but omits all other land uses. In contrast, the macro model entails competition for land by all sectors. By a proper linking, the strength of the detailed agricultural model can be utilized without sacrificing the competition between sectors provided by the macro model.

The purpose of this paper is to provide a description of the linked system of models, with emphasis on how the models work together. Section two briefly describes the involved models individually, focusing on those aspects that are relevant for the linkage. Section three more thoroughly discusses how the models are

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[1] FP VI Integrated Project, Contract No. 003874 (GOCE). www.sensor-ip.eu

[2] The reader may be familiar with EURURALIS and SCENAR2020; two projects with similar cross sector modelling ambitions. SENSOR differs from the EURURALIS project which uses only a cross sector model [11]; [14] and it adds to the SCENAR2020 study a better linking system and the inclusion of other sector models than agriculture [15].

linked. Section four concludes the paper by attempting to generalize from the experiences of the linking exercise.

II. OVERVIEW OF THE MODELS

A. The macro- econometric model NEMESIS

The economic model that makes the distribution of land claims between the sectors on national level is called NEMESIS [2]. It is a detailed macro-econometric model built for each country of the EU27 (plus Norway), which uses as main data source EUROSTAT, and specific databases for external trade (OECD, New CRONOS), technology (OECD and EPO) and land use (CORINE 2000). NEMESIS is recursive dynamic with annual steps.

NEMESIS distinguishes 32 production sectors and each sector is modelled with a representative firm that takes its production decisions given its expectations on marginal production capacity expansion and input prices. Firms' behaviour includes also R&D investment decisions that modify inputs productivity and output characteristics.

On the demand side, the representative household's final consumption is influenced by household's disposable income, prices of the 27 different product categories, and demographic structure. Government (public) final consumption and its repartition between Education, Health, Defense and Other Expenditures, are also influenced by demographic changes.

NEMESIS land module directly includes the three sub-models SICK, TIM, and B&B. With these sub-models, NEMESIS calculates land claims by housing as well as commercial and industrial building, land claims for rail and road transport infrastructure, and land claims by tourism respectively.

B. The agricultural sector model CAPRI

The partial equilibrium model CAPRI [3] offers a detailed depiction of the agricultural sector on regional level in the EU, with approximately 250 regions and 50 agricultural products. Agricultural production in European regions is determined by a mathematical programming model, which maximizes gross value added of a representative regional farm subject to technological constraints and a behavioural quadratic cost term. The quadratic cost term is derived from Positive Mathematical Programming (PMP; [9]), but the methodology has been improved in several respects [10], [6]).

The market for agricultural products is modelled on member state level in the EU and for about 40 regions in rest of the world, represented by 18 bilaterally trading blocks with own agricultural trade policy instruments. Final demand is based on a Generalized Leontief expenditure system combined with a two-stage budgeting system (cf. [1]; [7]). The three sectors dairy, oil seed crushing and animal feed mixing, are modelled by profit function approaches.

CAPRI contributes to SENSOR by implementing many agricultural policy instruments and delivering highly differentiated results for agriculture in European regions.

C. The forestry model EFISCEN

The EFISCEN model [17] is a matrix transition model that assesses timber availability and projects European forest resource development. EFISCEN uses national forest inventory data as main input data. For each forest type that can be distinguished in the input data, a separate matrix is set-up. Each matrix consists of age- and volume-classes over which forest area is distributed. This distribution describes the state of the forest. During simulations, area transitions occur between matrix cells, which represent natural processes (e.g. increment, mortality) and human actions (e.g. forest management, afforestation, deforestation). EFISCEN receives information on forest area changes from DYNA-CLUE and wood demand from NEMESIS. EFISCEN then checks whether the demand can be satisfied and projects forest resource development under that demand.

Outputs from EFISCEN include forest area, growing stock, increment, age-class distribution, removals, natural mortality, dead wood, forest biomass and soil[3] carbon stocks for every five year time-step.

D. Spatial disaggregation of land use: DYNA-CLUE

DYNA-CLUE [19] is a dynamic model with annual time steps that projects land cover changes. It bridges the gap between the outputs of NEMESIS at the national level and the input requirements at sub-national level of CAPRI and EFISCEN by distributing the land use on member state level given by NEMESIS to a 1 km^2 grid for 16 land cover types. Further, DYNA-CLUE provides detailed land cover information for the

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[3] Via the linked soil module YASSO [12]

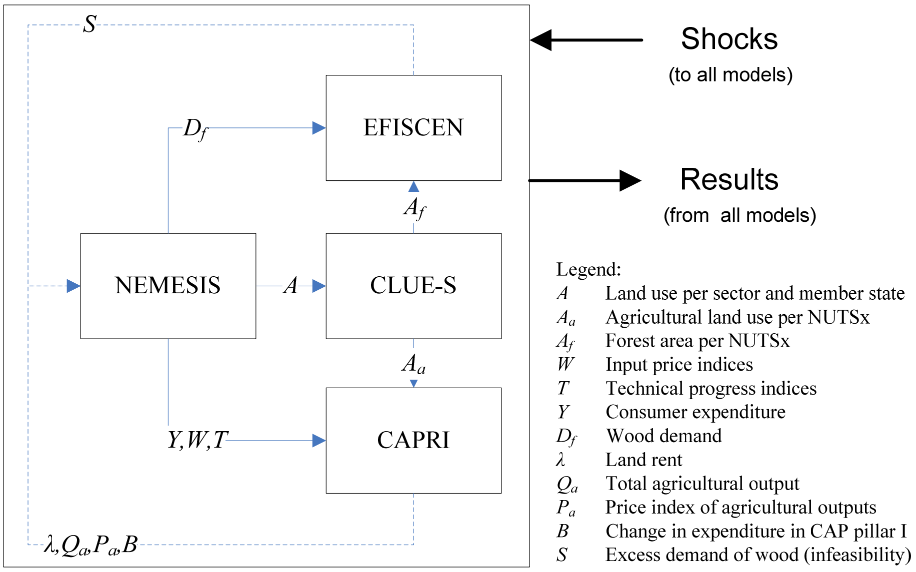

Figure 1: Flow chart of model linkages, details for shocks and results omitted

computation of sustainability impact indicators, and it allows the incorporation of spatial policies such as Natura2000 and the Less Favoured Area schemes.

The mechanisms of land use allocation included in the model can be divided in location characteristic and conversion characteristic. The location characteristic mechanism captures the suitability for each land use on each spot. It contains biophysical and socio-economic factors (inferred from statistical associations between CORINE2000 and a set of factors), and policy and neighbourhood effects [18]. Conversion characteristics are divided into conversion elasticities, determining the resistance of a land use type to change location, and transition sequences. A transition sequence is a set of rules that determine the possible sequences of land use conversions.

III. MODEL LINKAGES

A. Introduction

The models are linked to obtain a consistent, joint equilibrium, and to exploit the strengths of each model. This requires upstream as well as downstream linkages; macro policies and inter-sector interactions are implemented in NEMESIS. Their effects must thus be communicated downstream to the sector models in order to capture the effects on the individual sectors. On the other hand, sector specific policies and detailed behaviour are only implemented in the sector models. To compute the effects of such policies on other sectors and the economy as a whole, the sector models must also communicate upstream, where the effects can again be distributed to all sectors. The latter link is also required in order to obtain a consistent reaction of all sectors simultaneously to macro economic changes. Thus, bi-directional linkages are required.

The models cannot, for technical reasons, be integrated in one equation system and solved simultaneously. Instead of a simultaneous solution, an iterative recalibration solution for the linked system is used, similar to that which links the CAPRI supply and demand modules [3] and also to that described by [5] and [4].

The linkage between the upstream model NEMESIS and the downstream models DYNA-CLUE, CAPRI and EFISCEN are different depending on the direction that is considered. The downstream models need only to take the values from NEMESIS as given, exogenous data (multiplied by the link ratio of the baseline). In the opposite direction, specifically for the link from CAPRI into NEMESIS, the variable of the downstream model is not linked to an exogenous parameter but to an endogenous variable: NEMESIS already possesses an agricultural sector, thus overlapping CAPRI.

There are different options for the upstream link: either the relevant equations are deleted from the upstream model and replaced by parameters or (first order) approximations from the downstream model (cf. [4]). Another solution is to maintain the original equation in the upstream model, and iteratively recalibrate the parameters of the upstream equation to outcomes of the downstream model. We applied a combined approach, because it required less modifications of existing model code.

To facilitate convergence, a weighted average of previous iteration outcomes is used in certain critical links instead of only the outcome of the last iteration.

B. Implementation of linkages

Figure 1 shows how the model components are linked. The description of the iterative linkages can start with any of the models in the chain. In practice, the chain starts with CAPRI.

CAPRI obtains the amount of land A_a available for agriculture from DYNA-CLUE, and from NEMESIS, the vector of input price indices W, technical progress index vector T, and consumer expenditure vector Y. The received data is used to compute new sets of input prices, consumer prices, land constraints and technical I/O coefficients. After finding a (new) solution, CAPRI aggregates the dual values for land λ to the member state level, and also computes gross production of agriculture Q_a, the Laspeyres prices index of agriculture P_a, and the change in expenditure on agricultural support B (first pillar only), and sends this data set to NEMESIS.

NEMESIS uses this information (i.e. λ, $Q_{a\ and}\ P_a$) to recalibrate its land demand function for agriculture, and to replace its equations for total agricultural output and prices equations by constants corresponding to the results (Q_a, P_a) from CAPRI. The land demand function for agriculture in NEMESIS is determined by equation (1) below, where, for each iteration i, λ^i is the land price, C^i_{others} an index of other agricultural inputs cost, A_i is the land demand for agriculture and c^i and b are parameters.

$$A^i = c^i \left(\frac{C^i_{\text{others}}}{\lambda^i} \right)^b \tag{1}$$

In fact, the land demand function in NEMESIS is more complex, because NEMESIS is a dynamic model. The variable A denotes the long term desired level of land, and it enters with a time index in another equation with partial adjustment from period t-1.

Agricultural land prices per country (λ) are endogenous variables in CAPRI and NEMESIS and an iterative procedure is necessary to find the joint equilibrium land price. When NEMESIS begins iteration i, the land demand is shifted in such a way that, if considered alone, at the land demand (A) and others inputs cost (C_{others}) sent to CAPRI in iteration $i-1$, it would have returned the actual CAPRI land rent in iteration i. This implies computing c^i as shown in equation (2):

$$c^i = A_a^{i-1} \left(\frac{C^{i-1}_{\text{others}}}{\lambda^i} \right)^{-b} \tag{2}$$

NEMESIS is then solved including the re-calculated parameter c^i (see equation 2) in equation (1), with agricultural output and price index fixed to the last solution of CAPRI.

EFISCEN receives national demand for wood D_f, from NEMESIS and forest area A_f from DYNA-CLUE. D_f is converted into physical units and from A_f changes in forest area are calculated, which are then added or subtracted from the forest area in EFISCEN. EFISCEN assesses whether the demand for wood can be satisfied and projects forest resource development. A feedback (S) is sent from EFISCEN to NEMESIS as a percentage deviation between D_f from NEMESIS and the wood removals by EFISCEN at the national level. NEMESIS uses these results from EFISCEN to constrain D_f so that it cannot exceed the demand for which EFISCEN was run. All wood that cannot be harvested according to EFISCEN, will be imported from outside the EU in NEMESIS.

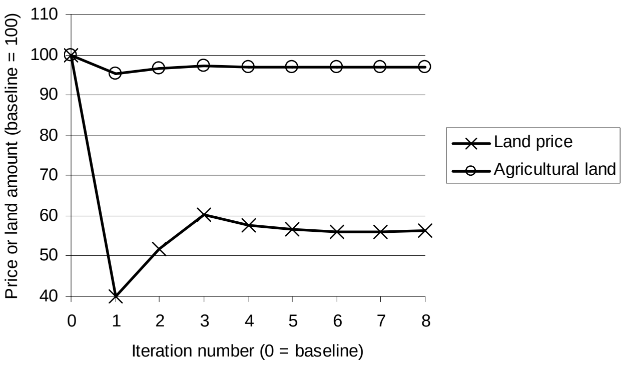

Figure 2.: Convergence pattern in a simulation with removal of agricultural support

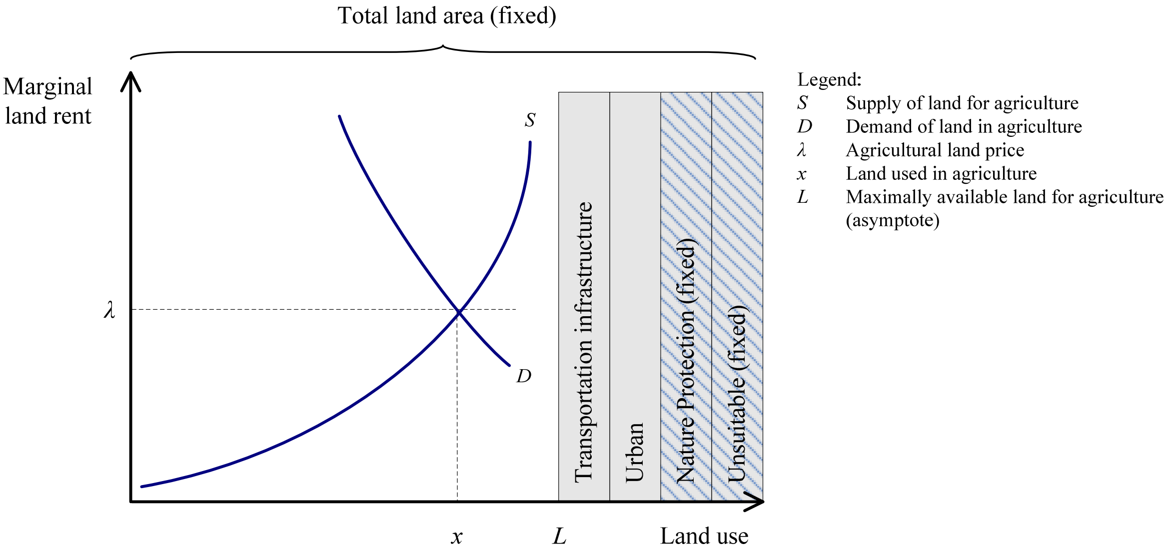

Figure 3: Land balance in SENSOR

The different models are run by different institutes. Data exchange takes place in the form of files written to a file server on the internet. The models regularly check the server to determine if a simulation is required, and in that case, download the output of the other models, recomputed parameters, simulate, and upload the new results. In that way, the rather time consuming computations can proceed with very little human intervention. Convergence in one simulation is generally achieved within a handful of iterations (Figure 2). Figure 2 also shows the impact of model linking on model variables. In Figure 2 agricultural land decreases with a few percentages. Although this seems small, it might have a relative strong effect on environmental indicators. If only CAPRI was applied this effect would not occur since land available for agriculture is fixed in CAPRI.

C. *Important feedbacks*

The linked system contains several feedback loops. Two such loops that deserve special attention are the common land balance and the endogenous research and development (R&D).

In the common land balance—the single most important feedback in the system—the total land area is divided into agriculture, forestry, urban (including tourism), transport infrastructure, and land unsuitable (i.e. areas with strong constraints in terms of soil quality and/or climate) for or legally exempted from exploitation. These sectors pose different claims on land, which are dealt with in a hierarchical manner. Relative to agriculture, the claims for urban, tourism and transport are superior and the claim from forestry is inferior (Figure 3. The superior land claims together with unsuitable and protected land (grey bars) limit the total amount of land available for agriculture (asymptote L) in each country.

Given *L*, the supply of land for agriculture *S* (see also [13]) depends on the (normalized) land price in agriculture λ. The price reflects the marginal cost of taking land into agricultural production. The agricultural land demand *D* reflects the marginal productivity of land in agriculture. The amount of land use in agriculture (x) is determined by the price equilibrium, $S(\lambda) = D(\lambda)$. The amount of land ($L - x$) that is not used by agriculture is potentially available for forestry (or other climax vegetation)[4].

A distinguishing feature of NEMESIS, compared to most macro economic models, is endogenous technical progress. Estimated functions relate national spending on R&D to factor productivity. In the linked system in SENSOR, this opens a most interesting possibility for simulating transfer of funds from agricultural support (Pillar I) to R&D, in line with the Lisbon agenda. In

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[4] *Land potentially available for forest* is modelled on the level of land balances, but consists of different land cover classes. These classes represent different stages in the succession to forest and the *actual forest area* itself.

the standard setting, the change in Pillar I expenditure (difference to baseline, vector *B* in figure 1) is linked to the national tax burden in NEMESIS, with a generally negligible effect. In a “Lisbon setting”, the change in CAP expenditure is instead invested in the R&D activity through subsidies. In that context, the about 40 billion euro currently spent on the first pillar can have a strong effect on productivity in all sectors in NEMESIS. Specifically, the factor productivity changes feed back to CAPRI via the vector *T* in figure 1, where they affect the cost of production by directly reducing the use of fertilizers, pesticides, seeds, animal feed, labour, machinery, buildings, energy, and other variable costs, and indirectly affecting production, income, and environmental impacts of agriculture.

D. Considerations for the baseline calibration

A special aspect of the model linkage relates to generating a consistent baseline (i.e. a simulation outcome that serves as a reference to evaluate other simulation outcomes). The models are so different in functional forms, starting data, spatial detail, assumptions and auxiliary data sources, that, for example, the agricultural sector in NEMESIS develops somewhat differently than it does in CAPRI (at the aggregated level). The main challenge for the baseline is to calibrate the linked system such that all models produce precisely the baseline outcome.

On the one extreme, the models could be forced to reproduce fully identical solutions. We call this the harmonization approach[5]. On the other extreme, the difference between the models could be accepted and interpreted as differences in definition of the underlying data and assumptions. In the latter case, the difference or the ratio between the linked items (here termed the link ratio) is computed in the baseline and maintained in simulations. We call this the differential approach. The differential approach is easy to implement, but may obscure true data problems and errors when applied to all linkages.

The chosen solution is a composite, including adjustments of the models to harmonize baselines and "freezing" of remaining differences. For NEMESIS, a baseline calibration program has been developed that treats the agricultural production and prices as exogenous, given by the CAPRI baseline, and adjusts parameters of price, domestic demand, imports and exports equations so that it reproduces the aggregated results of CAPRI. For CAPRI and DYNA-CLUE, the differential approach for baseline calibration is opted for, which implies computing the link ratio between the pairs of linked variables in the baseline, and then using that ratio in simulations to translate a change in the variable from upstream to a change in the downstream one. EFISCEN, finally, needs no special calibration procedure, since there is no overlap between the outcomes of EFISCEN and any of the other models.

IV. DISCUSSION

In SENSOR, a theoretical framework was developed that is capable of consistently linking a system of large scale models. In practice, not all components of a theoretically sound linkage could be established. Although it seems theoretically possible to link all variables where there is an overlap between models’ outputs or where the output of one model serves as input in another, only a handful of such links could be implemented within the present project, due to restrictions on resources. In particular, linkages of prices of labour and capital, external trade, and the input structure of agriculture are still absent. Below we explain why these linkages are absent, and what could possibly be done about it in the future.

The prices of labour and capital are endogenous in NEMESIS, whereas they are only implicitly present in CAPRI, which works with a combination of gross value added and a non-linear cost term. The cost term is derived from Positive Mathematical Programming (see e.g. [9]) to calibrate the agricultural supply module to observations and to impose realistic supply behaviour. The calibration method together with the lack of labour and capital in the model implies that the costs for labour and capital are embedded in a lump sum costs term, which is really a behavioural term also containing all other factors influencing producer supply behaviour. Thus, in this respect, the downstream model is less detailed than the upstream one, which causes a problem. To properly link the models, this cost term should be shifted, so as to reflect changes of prices of labour and capital in NEMESIS. The magnitude of the possible error is difficult to assess.

Both NEMESIS and CAPRI feature endogenous external trade. Since CAPRI has a comparatively sophisticated trade model, the external trade of agriculture in

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[5] We are not familiar with any publication that treats the general problem of calibrating a linked system of models. The terms used here, i.e. “harmonization” and “differential”, were introduced to fill the gap.

NEMESIS should be linked with that in CAPRI. This possibility should be further explored in future research.

Finally, CAPRI contains a much more detailed technology of agriculture than NEMESIS, and is thus capable of delivering more precise forecasts of changes in inputs. Use of inputs by the agricultural sector is endogenous in NEMESIS and information from CAPRI is presently not exploited in NEMESIS. Similar to the case of external trade, the difference in agricultural input use between the models could be, but has not been, evaluated ex-post in order to assess the size of the possible error.

Though not a fully theory-consistent link could be implemented in SENSOR, the system still provides significantly extended capabilities compared to the stand-alone models. With the linked system, impacts at sector level of general economic policies and developments can be analysed. Most importantly, the system captures the essential ingredients of the competition for land by different sectors. Policies that are directed towards any individual sector inevitably affect the regional land balance, and thus all other land-based sectors. However, land balances are not the only links implemented in the SENSOR modelling approach. Other linkages are e.g. between CAPRI and NEMESIS input prices and GDP (see Figure 1). Hence, analysis of, for example the simultaneous impact of bio-energy policies on the energy demand and supply sectors inside NEMESIS, wood production and forest resource development in EFISCEN and agricultural production in CAPRI, becomes possible. Another important property of the system is the possibility to link sector policies to national innovation policies, highlighting the trade-off between research investments and, for example, agricultural protection.

Last but not least, the process of developing the system has lead to accumulation of new insights in the principles of model linking, which may prove beneficial not only to SENSOR but also in a wider perspective. It has, however, also shown how much effort is involved in linking up large scale systems, where detailed knowledge of all components is required. A final word, fitting the recursive structure of the linkage project:

> Hofstadter’s law:
> *It always takes longer than you expect, even when you take into account Hofstadter's Law.*
> ([8], p. 152)

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