Croatian Operational Research Review
CRORR **16:1**(2025), 65–72

Calculation of ecological land-footprint – based on the input-output model and focusing on the imported commodities

Imre Dobos[1] and **Brigitta Tóth-Bozó**[1,*]

[1] *Department of Economics, Budapest University of Technology and Economics, H-1111 Budapest, Műegyetem rkp. 3., Hungary*
E-mail: ⟨{dobos.imre, bozo.brigitta}@gtk.bme.hu⟩

Abstract. The ecological footprint has been a crucial ecological indicator for more than two decades, and the methodology for calculating it has developed significantly over the years. However, some issues and shortcomings still need to be addressed and specified further. This paper focuses on the embedded land requirements of imported commodities in input-output modelling approaches. We propose a refined model to overcome the shortcomings of two former models. Our model quantifies the embedded ecological land-footprint of imported commodities and their allocation between direct final consumption and production. In addition, we allocate the latter again among final consumption and exports using the framework of linear algebra and matrix arithmetic. We also propose ways of extending the model to overcome the general but misleading assumption in the literature that imported commodities have an equal per unit ecological footprint to domestic products, an approach that is based on the idea that trading partners have the same technological background.

Keywords: ecological land-footprint, imported commodities, input-output model

Received: June 9, 2024; accepted: December 6, 2024; available online: February 4, 2025

DOI: 10.17535/crorr.2025.0006

Original scientific paper.

1. Introduction

Our methodology used needs to be explained: input-output modelling is used to show the ecological land-footprint defined by the land use approach. Given that one of the by-products of the Leontief input-output model is the land area used, it is suitable for defining a static ecological land-footprint. Since its first publication in the early 1990s, the ecological footprint has become the most popular ecological indicator [23, 28]. Its purpose is to determine the amount of land that nations use (expressed in global hectares) to satisfy the long-term needs of their populations while measuring the human pressure on ecosystems. In this context, it can be considered as an absolute measure of sustainability [11, 25]. Over time, the methodology has developed, and there are approaches that deal with the ecological footprint at regional, individual, and even organisational levels [22], which enrich the sustainability debate with new perspectives. The calculation of a static ecological footprint with an input-output model consists of the following steps: 1. Select the economic sectors and activities of the country to be examined by researchers who want to include them in their calculations. 2. Collect production data for each sector, including inputs (such as energy, water, and raw materials) and outputs (such as products and waste). 3. Organise the data into an input-output table that describes the dependencies between the different sectors and the number of inputs and outputs. 4. Supplement the input-output table with various data needed to calculate the

*Corresponding author.

footprint, such as the quantity of carbon dioxide emissions or energy use. 5. Calculate the footprint using the data in the table and the data added in the previous step, which measures the ecological impacts caused by economic sectors. The paper contains the following sections: Section 2 presents the literature review and the examined models. In section 3, we present a refined method for calculating ecological footprint with the input-output model, and section 4 concludes with the results of the paper.

2. Literature review

The concept of the ecological footprint has become one of the most widely used indicators of land use, alongside other popular terms like the circular economy and sustainable development. Although many models are less commonly applied today, they could be revived with modern enhancements. One such model is the original Leontief model, which did not initially include environmental factors but is suitable for calculating land use. Leontief later incorporated environmental aspects by presenting a static input-output model with pollution factors [16]. In this study, we calculate the land-related ecological footprint, building on two influential studies in the field. Our approach constructs the footprint based on vectors of final consumption, exports, and directly imported products consumed within a given period. The studies by Bicknell et al. [3] and Ferng [10] advanced the methodology of input-output models, providing the foundation for further developments. Csutora and Vetőné Mózner [5] applied a similar static input-output model to determine carbon emissions at the industry level, while Dobos [8] offered methodological critiques of these models. Leontief's model [17] provides a comprehensive analysis of the circular economy and continues to gain relevance today [14, 18, 19, 29]. While Leontief originally introduced the static input-output model with environmental factors, recent works have attempted to make the static footprint model dynamic [6]. Input-output models can be used to approach the ecological footprint in both static and dynamic forms, and in this study, we focus on the static calculation method. Lenzen et al. [15] examined the environmental relevance of input-output models, especially in relation to ecological footprint calculations, while Wiedmann and Barrett [30] reviewed the ecological footprint indicator, discussing its advantages, limitations, and the role of input-output models. We focus particularly on land use models, such as those explored by Hubacek and Sun [13], Ferng [10], Bicknell et al. [3], and Eder and Narodoslawsky [9]. Several studies, including Hubacek and Giljum [12] and Turner et al. [27], applied static methods to calculate the ecological footprint, focusing on pollution and land use. They concluded that importing products from industrialised countries significantly contributes to developing countries' natural environment degradation. Wiedmann and Barrett [30] also explored various interpretations and calculation methods for the ecological footprint, emphasising how input-output models can improve footprint calculations. Furthermore, research by Gao and Tian [21] examined greenhouse gas emissions in China from 1980 to 2030, using ecological footprint and input-output models to identify key factors driving the growth of emissions. Bringezu et al. [4] studied sustainable production and biofuels, using input-output models to assess biofuels' ecological and social impacts compared to other energy sources. These examples demonstrate the broad application of ecological footprint calculations and input-output analysis in the literature. Numerous studies provide specific calculations of ecological footprint. For instance, Abbood et al. [1] used an input-output model to calculate the carbon and energy footprint of the U.S. manufacturing system, quantifying the life-cycle impacts of U.S. manufacturing activities in the context of international trade. Specific case studies include analyses of ecological footprint for Malaysia [2], Finland [20], Japan [26], and China [31]. The application of ecological footprint in various regions illustrates the adaptability of input-output models to different environmental and economic contexts. Additionally, the Higgins Sustainable Growth Index incorporates the ecological footprint as a key variable, providing another practical application of the concept [24]. In the next section, we analyse two influential studies on ecological land-footprint: Bicknell et al. [3] and Ferng [10]. Bicknell's study was the first to model land use by considering whether it is driven by imports or domestic production. The model calculates the share of land allocated to consumption, including three types of land associated with imports: land for final direct consumption, land entering production for consumers, and land indirectly transferred from imports to exports. Ferng's work builds on this by introducing a land multiplier to improve the calculations [10]. The key difference between the two studies is that Ferng models land as a consumable resource rather than a primary input, and they differ in how they allocate imported land between final consumption and exports. One limitation of these models is the inability to partition sectoral imports between final consumption and exports linearly.

3. A refined method for calculating ecological footprint with the input-output model

When calculating the ecological footprint using empirical data, a relevant problem is the lack of data for the other countries. Therefore, it is proposed to substitute the data of the country under study for the data of the other countries, thereby facilitating the calculations. Given that the ecological footprint aims to capture the total direct and indirect resource use embodied in final consumption, input-output models provide an ideal accounting framework. Bicknell's model [3] was the first to address how to allocate imported land between final consumption and exports. Ferng [10] refined this by introducing a land multiplier, but even this method does not fully resolve the issues. In our study, we describe the mathematical contributions of these works and propose improvements to better account for the embedded footprint of imports, addressing differences in technological backgrounds and their impact on ecological footprint calculations. The basis of input-output analysis is a set of sectoral disaggregated economic accounts that identify the inputs and outputs of each sector. This method allows for the quantification of interdependencies within the economy, using straightforward mathematical routines to trace all direct, indirect, and induced resource use within consumption [16, 21]. The methods of Bicknell [3] and Ferng [10] differ in their approach to calculating the land requirements of imports used indirectly for consumption and exports. Bicknell allocates imports across sectors based on final consumption and exports, while Ferng reduces total output by exports, leaving the relevance of imports for production ambiguous. The first case presented by Bicknell [3] treats land as a resource, where specific land use is calculated per unit of output. Ferng's model assumes intra-sectoral exchange and incorporates land use in addition to exports. For a standard inter-sectoral model, this distinction is crucial, particularly in whether land use is considered in terms of the import or export columns. A more detailed comparison of the two models can be found in the work by Dobos and Tóth-Bozó [7]. In the next section, we will present the mathematical background for calculating land footprint based on input-output models. This background builds on the economic assumptions of previous studies, but offers a more precise mathematical formulation.

Our proposal is constructed in a framework shown in Table 1. The table differs from Table 3 of paper [7] as the imports are shared between the economies (countries) with that our hypothetical economy is in commercial relations - such type of modelling can be found in regional economics. Let us assume that there n sectors in the national economy are modelled and that there are m different further economies that have a commercial relationship with our economy. As before, the gross output of the economy is denoted by x, c vector is the final consumption, exp vector represents the exports, while X is cross-sectoral use. The vector l shows the land demand of the economy. The X_{imp_i} matrix shows the commodities imported from the ith economy and used by the different sectors of our economy, while the c_{imp_i} vector represents commodities imported from the ith economy to the final consumption of our national economy.

Vectors v and v_c show added values. The imp_i vectors represent commodities imported in total to the examined national economy, i.e., $imp_i = X_{imp_i}1 + c_{imp_i}$, where vector 1 denotes the summing vector, each element of that is one.

	Sectors	Final consumption	Export	Total output, import	Land (ha)
Sectors	X	c	exp	x	l
Country 1	X_{imp_1}	c_{imp_1}		imp_1	
Country 2	X_{imp_2}	c_{imp_2}		imp_2	
...	...	...		...	
Country m	X_{imp_m}	c_{imp_m}		imp_m	
Added value	v	v_c			
Total output	x				

Table 1: *An input-output table for a national economy with foreign trade.*

Where

- X_{imp_i} is the output from imported goods from the ith country, $i = 1, 2, ..., m$;
- c_{imp_i} is the final consumption from imported goods from the ith country, $i = 1, 2, ..., m$;
- v is the total added value vector with n dimension;
- v_c is the added value for final consumption with n dimension;
- x is the total output in the economy;
- imp_i is the total import from the ith country, $i = 1, 2, ..., m$;
- l is the total land use in hectare;

Then construct the model input coefficients for the economy and imports:

$$A = X\langle x\rangle^{-1}, \quad A_{imp_i} = X_{imp_i}\langle x\rangle^{-1}, \qquad (i = 1, 2, ..., m) \tag{1}$$

With these coefficient matrices, we can obtain the following equations describing the economy:

$$x = Ax + c + exp, \quad imp_i = A_{imp_i}x + c_{imp_i}, \qquad (i = 1, 2, \ldots, m) \tag{2}$$

In this context, the model is essentially the same as the one of the Table 1, as $X_{imp} = \sum_{i=1}^{m} X_{imp_i}$,$c_{imp} = \sum_{i=1}^{m} c_{imp_i}$, we did not do anything other than arranging imports according to their sources.

Considering the ecological footprint, as we can see, the land multiplier in the Ferngian sense is only known to our modelled economy (for the other economies, we should be aware of the input-output models of each national economy). If we would know the other land multipliers as well, they would follow the following general form: $\langle l_i\rangle(I - A_i)^{-1}$, where matrix A_i is the sectoral relationship balance of i nation's economy and vector l_i is the land demand of that economy.

Based on that, the imports used by the economy we use can be summarised thus:

$$\sum_{i=1}^{m}\langle l_i\rangle(I - A_i)^{-1}imp_i = \sum_{i=1}^{m}\langle l_i\rangle(I - A_i)^{-1}A_{imp_i}x + \sum_{i=1}^{m}\langle l_i\rangle(I - A_i)^{-1}c_{imp_i} \tag{3}$$

This expression is the same as in the earlier models, if $A = A_i$ and $l = l_i$, meaning that every economy is homogeneous in the sense that they have the same technology matrix and same area. In this case, the following relationship is fulfilled: $imp = \sum_{i=1}^{m} A_{imp_i} x + \sum_{i=1}^{m} c_{imp_i}$, which means that we sum up the imports regardless of their origin. Further analysis is conducted on this aggregate model where $A_{imp} = \sum_{i=1}^{m} A_{imp_i}, c_{imp} = \sum_{i=1}^{m} c_{imp_i}$.

So the model is $x = Ax + c + exp$ and $imp = A_{imp}x + c_{imp}$.

And one may solve this model to obtain the total output: $x = (I - A)^{-1}c + (I - A)^{-1}exp$ and $imp = A_{imp}(I - A)^{-1}c + A_{imp}(I - A)^{-1}exp + c_{imp}$. Here, the first system of equations describes the domestic production, while the second one shows imports as a function of final domestic consumption, exports and products directly imported for final consumption. We can determine the land demand by multiplying the domestic equations by the diagonal matrix of the domestic area, while applying the land multiplier to the imported products.

With this calculation:

$$\langle l \rangle x = \langle l \rangle (I - A)^{-1}c + \langle l \rangle (I - A)^{-1}exp \tag{4}$$

the following expressions are obtained:

$$\langle l \rangle (I - A)^{-1} imp = \langle l \rangle (I - A)^{-1} A_{imp} (I - A)^{-1} c + \langle l \rangle (I - A)^{-1} A_{imp} (I - A)^{-1} exp + (I - A)^{-1} c_{imp} \tag{5}$$

Thus, we have five layers of land requirements:

- $\langle l \rangle (I - A)^{-1}c$: domestic land requirements of final consumption,
- $\langle l \rangle (I - A)^{-1}exp$: domestic land requirements of export,
- $\langle l \rangle (I - A)^{-1}c_{imp}$: embedded land requirements of direct imports serving final consumption,
- $\langle l \rangle (I - A)^{-1} A_{imp} (I - A)^{-1}c$: embedded land requirements of indirect imports (for the production sector serving final consumption),
- $\langle l \rangle (I - A)^{-1} A_{imp} (I - A)^{-1}exp$: embedded land requirements of indirect imports (for the production of exported products).

In the light of these categories, we can classify land requirements into two groups: (1) domestic demand for land use that is linked to final consumption, and (2) land demand for foreign consumption that is attached to exports and thus does not appear in domestic consumption. This latter land demand can be counted as a transit item, since after being imported, it will leave the country as export and will not enter the country and its economy, so it will not be part of the land requirements of the country.

We will now compare our **proposed** approach with the two previous models, as shown in the 2nd table.

	[3]	[10]	Proposed model
Domestic land requirements of final consumption	$l(I-A)^{-1}c$	$\langle l\rangle(I-A)^{-1}c$	$\langle l\rangle(I-A)^{-1}c$
Embedded land requirements of direct imports serving final consumption	$l(I-A)^{-1}\langle c_{imp}\rangle$	$\langle l\rangle(I-A)^{-1}c_{imp}$	$\langle l\rangle(I-A)^{-1}c_{imp}$
Embedded land requirements of production	$l(I-A)^{-1}A_{imp}\langle x\rangle$	–	–
Embedded land requirements of indirect import (for the production serving final consumption	$l(I-A)^{-1}A_{imp}\cdot$ $\cdot\langle x\rangle\langle c\rangle\langle c+exp\rangle^{-1}$	$\langle l\rangle(I-A)^{-1}\cdot$ $\cdot A_{imp}(x-exp)$	$\langle l\rangle(I-A)^{-1}\cdot$ $\cdot A_{imp}(I-A)^{-1}c$
Domestic land requirements of exports	–	$\langle l\rangle(I-A)^{-1}exp$	$\langle l\rangle(I-A)^{-1}exp$
Embedded land requirements of indirect imports (for the production of exported products)	–	–	$\langle l\rangle(I-A)^{-1}A_{imp}\cdot$ $\cdot(I-A)^{-1}exp$

Table 2: *The categories to be captured by the papers.*

It is immediately apparent that paper [10] did not specify the land requirements related to the import demand of exports, which is a barrier for precisely determining the land requirements of the imported products used for production. As

$$(x-exp)-c=Ax\geq 0 \tag{6}$$

the weighted land demand in our proposed model will be lower than the figure arrived at by the Ferngian model. A numerical comparison of the three models in Table 2 can be found in work [7].

Having expanded the refined Leontief's input-output model by taking into account the land footprint, we summarise the obtained results in the conclusion section. These results enable a more accurate footprint calculation.

4. Conclusion

A slight inaccuracy found in previous modelling has now been corrected. By our method we have calculated lower footprints, which significantly modifies the earlier overestimation. The use of input-output model for calculating static ecological footprint may pose several mathematical difficulties. These include handling larger input-output tables, solving nonlinear equations, and analysing and visualising multidimensional data. In addition, the accuracy of the model may be questionable, as environmental impacts are often difficult to measure precisely and require estimation. Another difficulty of the input-output model is that it does not consider temporal changes, meaning it cannot model dynamic effects. Finally, the model may be sensitive to the quality and accuracy of input data, so the accuracy of the results depends on the quality of input data. Our result is that we have created a newly formulated land footprint calculation model that features an input-output model. By our method we calculated lower footprints in work [7], which significantly modifies the earlier overestimation. We have also shown that imports could be generally managed to calculate the footprint, but this would require a massive calculation since all the technical coefficients of each national economy concerned would need to be known. The other authors assume that different commodities are produced under the same technological conditions, and thus the same land requirements, in every country. In a subsequent analysis, the presented model is appropriate for calculating the ecological footprint of a real economy (furthermore, it can also be used for calculating other footprints, like the carbon footprint). Another possible extension of the model is afforded by the dynamism of the footprints, that is, the impact of accumulation and investment processes on the footprint. For this, the dynamic version of the Leontief model can serve as an appropriate method.

References

[1] Abbood, K., Egilmez, G. and Mészáros, F. (2022). Multi-region Input-Output-based Carbon and Energy Footprint Analysis of US Manufacturing. Periodica Polytechnica Social and Management Sciences, 31(2), 91-99. doi: 10.3311/PPso.19554

[2] Begum, R. A., Pereira, J. J., Jaafar, A. H. and Al-Amin, A. Q. (2009). An empirical assessment of ecological footprint calculations for Malaysia. Resources, Conservation and Recycling, 53(10), 582-587. doi: 10.1016/j.resconrec.2009.04.009

[3] Bicknell, K. B., Ball, R. J., Cullen, R. and Bigsby, H. R. (1998). New methodology for the ecological footprint with an application to the New Zealand economy. Ecological Economics, 27(2), 149-160. doi: 10.1016/S0921-8009(97)00136-5

[4] Bringezu, S., Schütz, H., Arnold, K., Merten, F., Kabasci, S., Borelbach, P. Michels, C., Reinhardt, G. A. and Rettenmaier, N. (2009). Global implications of biomass and biofuel use in Germany–Recent trends and future scenarios for domestic and foreign agricultural land use and resulting GHG emissions. Journal of Cleaner Production, 17(S1), S57-S68. doi: 10.1016/j.jclepro.2009.03.007

[5] Csutora, M. and Vetőné Mózner, Z. (2024). The total cost of fossil inputs and outputs based on input-output tables–the example of China. Statisztikai Szemle, 102(2), 158-186. doi: 10.20311/stat2024.02.hu0158

[6] Dobos, I. and Tóth-Bozó, B. (2024). Ecological Footprint Calculation as a Land Demand: Based on the Dynamic Leontief Model. Periodica Polytechnica Social and Management Sciences, 32(2), 103-114. doi: doi.org/10.3311/PPso.21257

[7] Dobos, I. and Tóth-Bozó, B. (2024). Calculation of Ecological Land-Footprint–Based on the Input-Output Model and Focusing on the Imported Commodities. Research Square, Preprint. doi: 10.21203/rs.3.rs-3805321/v1

[8] Dobos, I. (2019). A Note on the Calculation of Ecological Footprint with Input-Output Model. Alkalmazott Matematikai Lapok, 36, 145-159.

[9] Eder, P. and Narodoslawsky, M. (1999). What environmental pressures are a region's industries responsible for? A method of analysis with descriptive indices and input–output models. Ecological Economics, 29(3), 359-374. doi: 10.1016/s0921-8009(98)00092-5

[10] Ferng, J. J. (2001). Using composition of land multiplier to estimate ecological footprints associated with production activity. Ecological Economics, 37(2), 159-172. doi: 10.1016/S0921-8009(00)00292-5

[11] Gao, J. and Tian, M. (2016). Analysis of over-consumption of natural resources and the ecological trade deficit in China based on ecological footprints. Ecological indicators, 61(2), 899-904. doi: 10.1016/j.ecolind.2015.10.044

[12] Hubacek, K. and Giljum, S. (2003). Applying physical input–output analysis to estimate land appropriation (ecological footprints) of international trade activities. Ecological Economics, 44(1), 137-151. doi: 10.1016/s0921-8009(02)00257-4

[13] Hubacek, K. and Sun, L. (2001). A scenario analysis of China's land use and land cover change: incorporating biophysical information into input–output modeling. Structural Change and Economic Dynamics, 12(4), 367-397. doi: 10.1016/S0954-349X(01)00029-7

[14] Keček, D., Mikulić, D. and Fotova Čiković, K. (2022). Economic contribution and integration of Croatian ICT sectors. Croatian Operational Research Review, 32(2), 161-172. doi: 10.17535/crorr.2022.0012

[15] Lenzen, M., Murray, S. A. and Korte, B. (2003). The environmental relevance of Link Input–Output. Ecological Economics, 44(1), 69-82. doi: 10.1016/j.ecolecon.2006.12.002

[16] Leontief, W. (1970). Environmental Repercussions and the Economic Structure. An Input-Output Approach. The Review of Economics and Statistics, 52, 262-271. doi: 10.2307/1926294

[17] Leontief, W. (1986). *Input-output economics.* Oxford: Oxford University Press.

[18] Lonca, G., Bernard, S. and Margni, M. (2019). A versatile approach to assess circularity: The case of decoupling. Journal of Cleaner Production, 240, 118174. doi: 10.1016/j.jclepro.2019.118174

[19] Lucas, P. and Vardon, M. (2021). Greening the Recovery to Make it Last. PBL Netherlands Environmental Assesment Agency Policy Report 5th Policy Forum on Natural Capital Accounting for Better Decision Making. url: www.pbl.nl/en [Accessed 8/12/2024]

[20] Mattila, T. (2012). Any sustainable decoupling in the Finnish economy? A comparison of the pathways and sensitivities of GDP and ecological footprint 2002–2005. Ecological Indicators, 16, 128-134. doi: 10.1016/j.ecolind.2011.03.010

[21] Miller, R. E. and Blair, P. D. (2009). *Input-output analysis: Foundations and extensions, 2nd Edition.* Cambridge University Press.

[22] Global Footprint Network (2012). Footprint Basics – Overview. Global Footprint Network. url: www.footprintnetwork.org. [Accessed 4/19/2018]

[23] Rees, W. E. (1992). Ecological footprints and appropriated carrying capacity: What urban economics leave out. Environment and Urbanization, 4, 120-130. doi: 10.1177/095624789200400212

[24] Steblyanskaya, A. A. Wang, Z. Denisov, A. and Bragina, Z. (2020). Company sustainable growth as the result of interaction between finance, energy, environmental and social factors (in case of JSC "Gazprom"). St Petersburg University Journal of Economic Studies, 36(1), 134-160. doi: 10.21638/spbu05.2020.10

[25] Szigeti, C. Tóth G. and Szabó, D. R. (2017). Decoupling–shifts in ecological footprint intensity of nations in the last decade. Ecological indicators, 72, 111-117. doi: 10.1016/j.ecolind.2016.07.034

[26] Tsuchiya, K., Iha, K., Murthy, A., Lin, D., Altiok, S., Rupprecht, C. D., Kiyono, H. and McGreevy S.R. (2021). Decentralization & local food: Japan's regional Ecological Footprints indicate localized sustainability strategies. Journal of Cleaner Production, 292, 126043. doi: 10.1016/j.jclepro.2021.126043

[27] Turner, K., Lenzen, M., Wiedmann, T. and Barrett, J. (2007) Examining the global environmental impact of regional consumption activities—Part 1: A technical note on combining input–output and ecological footprint analysis. Ecological Economics, 62(1), 37-44. doi: 10.1016/j.ecolecon.2006.12.002

[28] Wackernagel, M. and Rees, W. E. (1996). Our ecological footprint: Reducing human impact on the Earth. Philadelphia: New Society Publishers.

[29] Wiebe, K. S., Harsdorff, M., Montt, G. and Simas, M. S. Wood, R. (2019). Global circular economy scenario in a multiregional input–output framework. Environmental science & technology, 53(11), 6362-6373. doi: 10.1021/acs.est.9b01208

[30] Wiedmann, T. O. and Barrett, J. R. (2010). A review of the ecological footprint indicator—Perceptions and methods. Sustainability, 2(6), 1645-1693. doi: 10.3390/su2061645

[31] Zhou, X., Imura, H. and Shirakawa, H. (2006). Who is responsible for what: regional Ecological Footprint calculation for China with special emphasis on interregional dependency. In: *Third World Congress of Environmental and Resource Economist.*