Untangling the Greenhouse Gas Emission – Output Dilemma in the Livestock Sector: A Group Efficiency Perspective

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Abstract

Future human well-being is inextricably linked to adequate food provision. As the global demand for food will rise until at least 2050, the necessity of growing food supply will become progressively imperative. The problem of climatic change complicates this food supply challenge, as agricultural production is a significant source of greenhouse gases. One should thus improve global agricultural production while taking into account its harmful effects on the environment. Agronomists and biologists, on the one hand, and economists, on the other hand, have studied this problem from the perspective of the technological possibilities of the individual farm. For agronomists and biologists, this translates into the development of new efficient technologies. For economists, this implies the comparison of the performance of farm to a hypothetical best practice benchmark. Our research intends to shift the perspective from the individual farm level to the group level and allowing for reallocation possibilities of inputs between farms. We econometrically estimate the relationship between the European livestock output and the current European greenhouse gas emissions if there is (no) improvement of technical efficiency and reallocation of inputs is (in)feasible. Our results suggest that reallocation of production factors may increase output by 15-42%.

1. Introduction

Since the publication of *Our Common Future* by the World Commission on Environment and Development (WCED) in 1987, the notion of *sustainable development* has come to the fore in political discussions. The WCED advised a “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (WCED, 1987, p. 43). This widely used description of sustainable development (Kates et al., 2005) entails that human well-being ought to be nondeclining in time.

Food production is the primary driver of human well-being and thus of sustainable development. As, due to rising world population pressure and changing food consumption patterns, the global demand for food will increase until at least 2050, the necessity of growing food supply will become more and more important (Godfray et al., 2010). Concretely, global food production would roughly need to double to adjust to the “2050 World” with its circa nine billion inhabitants (World Bank, 2008).

Also environmental concerns (e.g., the exhaustion of natural resources and global warming) threaten to hamper the goal of nondeclining human well-being. Moreover, the problem of climatic change severely complicates the food supply challenge. Global agricultural production contributes to 30-35% of the total worldwide anthropogenic emission of greenhouse gases (GHG; Foley et al., 2011). In light of sustainable development, one should therefore improve global agricultural production while taking into consideration its effects on the environment (Ang and Van Passel, 2012).

2. Objectives

The sustainable production of food has become a well-studied subject for agronomists and biologists. Livestock production plays an important role, accounting for at least half of GHG emission in agriculture, mainly due to the use of manure in anaerobic conditions, processes of enteric fermentation, and expanding land use for animal feed production (Steinfeld et al., 2006; Vergé et al., 2007). Crop production intended for human consumption also contributes to GHG emissions. Nevertheless, 35% of total crop production is allocated to animal feed (Foley et al., 2011). We therefore delimit this section (and our research proposal) to livestock production. Several strategies are suggested to deal with the looming “2050 World” (Foley et al., 2011; Gill et al., 2010; Smith et al., 2008; Soussana et al., 2007). First, one should improve the sink properties of grasslands on which cattle reside. Second, by selecting the appropriate crop varieties and fertilizers, extending crop rotation, and exploring agroforestry potential, one is able to simultaneously increase yields and enhance CO_2 storage in animal feed production. Third, one should focus on livestock production itself through enhanced species selection (with the consideration of novel biotechnological possibilities), breeding practice, animal health, manure management, and feed supplements affecting the GHG formation in the rumen of cattle (note that this latter option is still at a preliminary stage). Finally, additional agricultural expansion at the expense of tropical forests should be avoided.

Also economists turned their attention to the tremendous challenge of increasing agricultural production while taking into account GHG emission. One usually views this intertwining problem from an extended productive efficiency perspective. Econometrists try to statistically relate the performance of an economic entity to its input use. Because textbook microeconomics (e.g., Mas-Colell et al., 1995) treats firms as successful profit-maximizing agents, conventional econometric techniques regard deviations of observations from the production function as statistical noise. However, firms are highly variable in achieving this objective due to, for example, differing organizational structures (Mathijs and Swinnen, 2001) and managerial characteristics (Van Passel et al., 2007). Consequently, productive efficiency analysts postulate that the deviations of the observations could be attributed to inherently inefficient behavior (Farell, 1957). The performance of the firm is compared to the performance of a hypothetical best practice benchmark. Expressed as a ratio, this comparison represents the technical efficiency of the firm. From the viewpoint of our status quaestionis, we are interested in the following: What should the maximum output of the farm be, given a certain amount of GHG emission? Therefore, productive efficiency analysts do not only consider conventional inputs (i.e., land, labor and capital), but also environmental inputs (in which harmful emissions are treated as inputs). This extended productive efficiency perspective is amply applied to farms. Examples include Kuosmanen and Kuosmanen (2009), Oude Lansink and Bezlepkin (2003), Oude Lansink and Silva (2003), Reinhard et al. (1999, 2000 and 2002), Van Passel et al. (2009), and Yang (2009).

The growing body of literature by agronomists and biologists, on the one hand, and economists, on the other hand, has one common characteristic: It focuses on the technological possibilities of the individual farm. For agronomists and biologists, this means the invention and adaptation of new efficient technologies. For economists, this translates into reaching the production frontier. These studies are in our opinion absolutely indispensable to tackle our research question. Nonetheless, it also reflects a vast belief in the potential of technological progress.

This more optimistic outlook, however, could fail to materialize. In reality, technologies may work insufficiently or may be adapted too slowly. In the most pessimistic scenario, they may even not progress at all. Farms would then use the same technologies as before and would remain equally technically inefficient. At first sight, this seems to imply a status quo and hence a failure of achieving our research question. If one takes the perspective of the individual farm, this will indeed be the outcome. However, given the global character of the research question, one should in our opinion put all options on the table. Concretely, one should consider the option of reallocation of inputs between farms. This possibility is very interesting, as reallocation of inputs within a group can increase the output of the group as a whole (Nesterenko and Zelenyuk, 2007). As an economist, one may pose the following bold question: What is the maximum European livestock output given the current European GHG emissions and the current technologies, if reallocation of inputs is possible?

Our study intends to provide creative solutions for the huge challenge of increasing agricultural production while reducing GHG emission by for the first time shifting the perspective from the individual farm level to the group level and allowing for reallocation possibilities of inputs. Our objective is to econometrically estimate the relationship between the European livestock output and the current European GHG emissions if (1) there is no improvement of technical efficiency and reallocation of inputs is infeasible, (2) there is improvement of technical efficiency and reallocation of inputs is infeasible, (3) there is no improvement of technical efficiency and reallocation of inputs is feasible, (4) there is improvement of technical efficiency and reallocation of inputs is feasible.

3. Methodology

This methodology section consists of two parts. First, we provide an overview of traditional productivity analysis applied to the individual firm level. Second, we describe which datasets are used.

3.1. Individual Production

The basic strategy of productive efficiency analysis is to formally link the output to the use of production factors. Next to land, labor and capital, the emission of CO_2-equivalents (CO_2-eq) is also considered a resource input in our model. If one argues that all firms show profit-maximizing and thus technically efficient behavior, farms do not structurally deviate from our estimated production function $f: \mathbb{R}_+^R \rightarrow \mathbb{R}_+$, so that

$$y_i = f(x_i, \beta) \cdot \exp(v_i) \quad (1)$$

where for all economic entities indexed with a subscript i, y_i represents the livestock output; x_i stands for the resource vector; β is the technology parameter vector to be estimated; v_i is a random error term, independently and identically distributed as $N\left(0, \sigma_y^2\right)$, including events beyond the control of the farmers (e.g., diseases and weather conditions).

Concretely, this means that a (log-linearized) Cobb-Douglas production function can easily be estimated by an Ordinary Least Squares regression.

On the other hand, a production frontier that does take into account the possibility of technically inefficient farms by means of u_i (a nonnegative random error term, independently and identically distributed as $N\left(\mu, \sigma_y^2\right)$, capturing time-invariant technical inefficiency in production) can be stochastically assessed in the following way (Aigner et al., 1977):

$$y_i = \tilde{f}(x_i, \beta) \cdot \exp(v_i - u_i) \quad (2)$$

Note that we put a tilde on the f ($\tilde{f}$) to differentiate from (1). The technical efficiency TE_i with regard to (2) is a function of u_{it}:

$$TE_i = y_i / \left[\tilde{f}(x_i, \beta) \cdot \exp(v_i)\right] = \exp(-u_i) \quad (3)$$

which can be estimated as follows (Battese and Coelli, 1988 and 1992):

$$\widehat{TE}_i = E[\exp(-u_i) | (v_i - u_i)] \quad (4)$$

(2) and (3) are output-oriented, as they express the ratio of observed to maximum feasible output.

3.2. Group Production

This part considers our four scenarios with respect to the production of the group, taking into account all hypothetical combinations of improvement of technical efficiency and resource reallocation. Figure 1 illustrates the *ceteris paribus* relationship between emission of CO_2-eq and livestock output when there is (no) improvement of technical efficiency and reallocation of production factors is (im)possible.

Scenario 1: No improvement of technical efficiency and infeasible reallocation of inputs

For the most pessimistic scenario, the production function of the group Y_A is:

$$Y_A = \sum_{i=1}^{I} y_i \tag{5}$$

Figure 1 also shows that livestock output does not substantially rise if the emission of CO_2-eq increases.

Scenario 2: Improvement of technical efficiency and infeasible reallocation of inputs

We infer the production frontier of the group as follows:

$$Y_B = \sum_{i=1}^{I} \tilde{f}(x_i, \beta) \tag{6}$$

The technological efficiency of the group $TE_{group,B}$ can be captured in the following way (Färe and Zelenyuk, 2003):

$$TE_{group} = \sum_{i=1}^{I} TE_i \cdot [y_{it} / \sum_{i=1}^{I} y_{it}] = \frac{|0A|}{|0B|} = \frac{Y_A}{Y_B} \tag{7}$$

Scenario 3: No improvement of technical efficiency and feasible reallocation of inputs

The corresponding production frontier Y_C can be calculated as a maximization problem:

$$Y_C = \max_{x_{ir}} \sum_{i=1}^{I} TE_i \cdot \tilde{f}(x_{ir}, \beta) \text{ subject to } \sum_{i=1}^{I} x_{ir}^* \leq \sum_{i=1}^{I} x_{ir} \tag{8}$$

in which x_{ir}^* stands for the optimal resource allocation that maximizes $\sum_{i=1}^{I} TE_i \cdot \tilde{f}(x_{ir}, \beta)$.

For each value of the resource use of the group of farms, one thus sets up a resource reallocation scheme that maximizes output at the group level. Note that output maximization from the group perspective does not imply output maximization from the viewpoint of the individual farm. Reallocation of resources in this way means that some farms may increase output, while others may decrease output.

The ratio of the current output to the maximized output in case of reallocation and no improvement of technical efficiency can be denoted as the *reallocative efficiency* RE_{group}. Concretely,

$$RE_{group} = \frac{|0A|}{|0C|} = \frac{Y_A}{Y_C} \tag{9}$$

Scenario 4: Improvement of technical efficiency and feasible reallocation of inputs

This scenario would yield the highest output for a given resource input vector. We infer the matching production frontier with the following maximization program (Nesterenko and Zelenyuk, 2007):

$$Y_D = \max_{x_{ir}} I \cdot \tilde{f}(x_{ir}, \beta) \text{ subject to } \sum_{i=1}^{I} x_{ir}^* \leq \sum_{i=1}^{I} x_{ir} \tag{10}$$

in which x_{it}^* stands for the optimal resource allocation that maximizes $\sum_{i=1}^{I} I \cdot \tilde{f}(x_{ir}, \beta)$.

Like (8), (10) maximizes output of the group for each hypothetical resource use level. However, unlike in (8), the group frontier function in (10) assumes that all individual farms are technologically efficient ($TE_i = 1$ for all i).

Finally, the ratio of the current output to the maximized output in case of reallocation and technological progress can be represented by the *reallocative technical efficiency* RTE_{group} (Nesterenko and Zelenyuk, 2007):

$$RTE_{group} = \frac{|0A|}{|0D|} = \frac{Y_A}{Y_D} \tag{11}$$

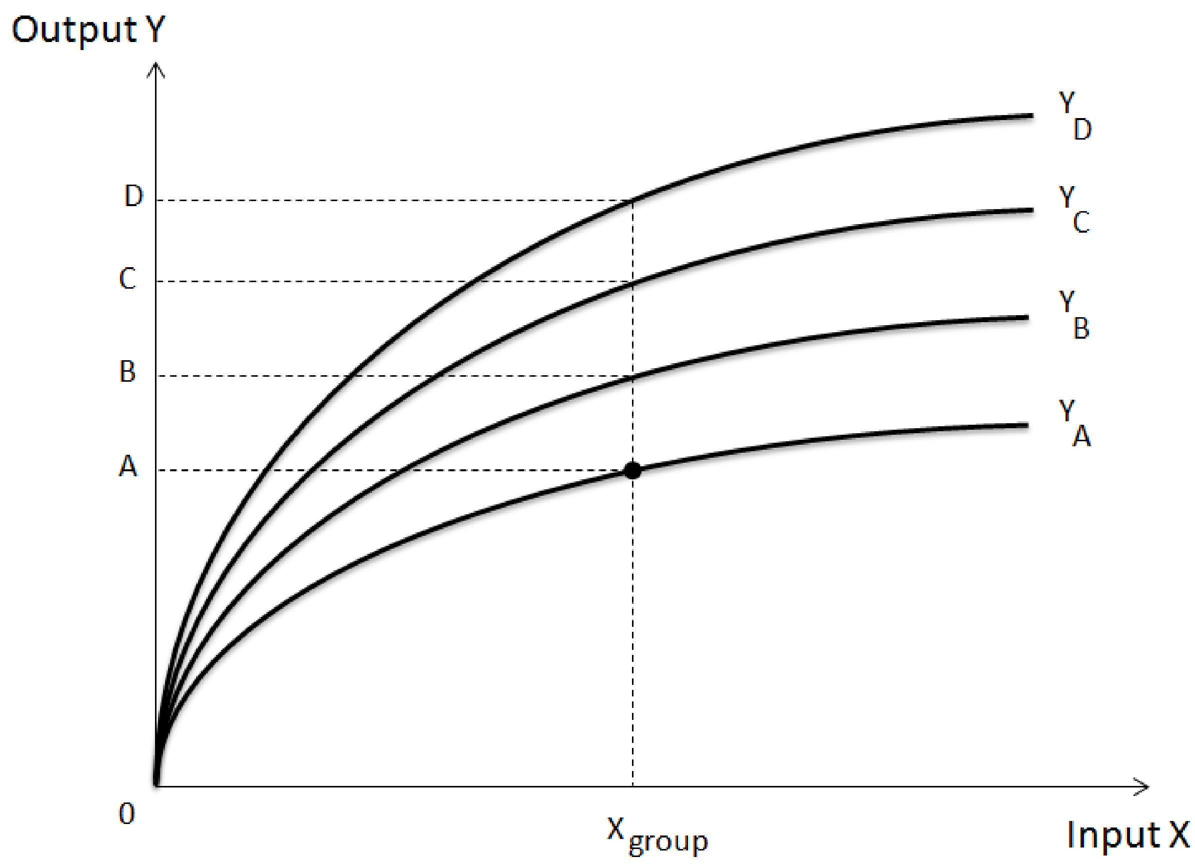

Figure 1: ***Ceteris paribus*** **relationship between emission of CO_2-eq and livestock output when (1) there is no improvement of technical efficiency and reallocation of inputs is infeasible (Y_A), (2) there is improvement of technical efficiency and reallocation of inputs is infeasible (Y_B), (3) there is no improvement of technical efficiency and reallocation of inputs is feasible (Y_C), (4) there is improvement of technical efficiency and reallocation of inputs is feasible (Y_D).**

3.3. Data

For the productivity analysis with regard to the first and second research objective, we use the European Farm Accountancy Data Network (FADN). This database provides the needed information concerning output, land, labor, capital at the NUTS2 level for circa 170.000 sample farms. The data with respect to the emission of CO_2-eq are more difficult to collect as these can only be calculated in an indirect way. For the EU-27, only calculations of the emission of CO_2-eq between 2003 and 2005 are available at the NUTS2 level (see Eurostat database). Because of the data availability, the economic entity is largely defined at the NUTS2 level[1] and limited to the year 2004.

4. Results

4.1. Individual Production

Table 1 shows the results of an OLS regression and stochastic frontier estimation of a log-linearized Cobb-Douglas production function that relates $\ln(y_i)$ of the economic entity i to its corresponding input vector $\ln(x_{ir}) = [\ln(x_{i,capital}), \ln(x_{i,land}), \ln(x_{i,labor}), \ln(x_{i,CO_2})]'$. $x_{i,capital}$, $x_{i,land}$, $x_{i,labor}$, and x_{i,CO_2} represent the capital (in €), land use (in ha), total labor input (in full-time person equivalent), and CO_2-eq emission without land use and land use change (in 1000 tons). According to the adjusted R^2, the OLS model can explain 92.44% of the results. Both models indicate a significant, positive relationship between output, on the one hand, and capital, labor, and CO_2-eq emission, on the other hand. Although the coefficients and standard errors seem to be of a similar magnitude, an additional likelihood-ratio test rejects the null hypothesis: H_0: $\sigma_u^2 = 0$ against its alternative hypothesis H_1: $\sigma_u^2 > 0$ at the 5% level. Because the stochastic frontier model cannot be reduced to the OLS model with normal errors, variations in technical efficiency consequently play an important role. The technical efficiencies of the economic entities differ considerably (ranging from 0.29 to 0.93 with a mean of 0.74 and a standard deviation of 0.14).

[1] All data are described at the NUTS2 level for the data on CO_2-eq emission. Although this is mostly the case for the FADN dataset, some are described at a slightly different level. Therefore, we correspondingly aggregated these data to the same level.

Table 1

	Ordinary Least Squares		Stochastic Frontier	
	Coefficient	Standard error	Coefficient	Standard error
Intercept	1.59**	0.85	1.47**	0.79
Inputs				
ln $(x_{i,capital})$	0.79***	0.06	0.84***	0.06
ln $(x_{i,land})$	0.04	0.05	0.00	0.04
ln $(x_{i,labor})$	0.09**	0.05	0.08**	0.05
ln (x_{i,CO_2})	0.09**	0.04	0.09**	0.04
Iterations	–		4	
Adjusted R^2	0.9244		–	
Number of observations	113		113	

Statistical significance is indicated at the 1% (***), 5% (**), and 10% (*) level.

4.2. Group Production

Scenario 1: No improvement of technical efficiency and infeasible reallocation of inputs

The group production if one cannot improve technical efficiency nor reallocate inputs is simply the sum of all outputs considered (see (5)). In 2004, the EU-27 livestock farms produced a combined output of $Y_A = € \ 246{,}942{,}600{,}780$.

Scenario 2: Improvement of technical efficiency and infeasible reallocation of inputs

If all economic entities perform at their production frontier without being able to reallocate inputs (see (6)), the EU-27 livestock farms could produce a combined output of $Y_B = € \ 340{,}312{,}385{,}465$. (7) defines the technical efficiency of the group $TE_{group} = \frac{Y_A}{Y_B} = 1.38$.

Scenario 3: No improvement of technical efficiency and feasible reallocation of inputs

Applying the Cobb-Douglas functional form to (8) yields the following maximization problem in case of no improvement of technical efficiency and feasible reallocation of inputs:

$Y_C = \max_{x_{ir}} \sum_{i=1}^{113} TE_i \cdot \exp(\theta) \cdot x_{i,capital}^{\alpha} \cdot x_{i,land}^{\beta} \cdot x_{i,labor}^{\gamma} \cdot x_{i,CO_2}^{\delta}$ subject to $\sum_{i=1}^{113} x_{ir}^{*} \leq \sum_{i=1}^{113} x_{ir}$

in which $\theta = 1.47$ represents the intercept, $\alpha = 0.84$, $\beta = 0.00$, $\gamma = 0.08$, and $\delta = 0.09$ are the coefficients of the stochastic frontier estimation, and x_{ir}^{*} stands for the optimal resource allocation that maximizes $\max_{x_{ir}} \sum_{i=1}^{113} TE_i \cdot \exp(\theta) \cdot x_{i,capital}^{\alpha} \cdot x_{i,land}^{\beta} \cdot x_{i,labor}^{\gamma} \cdot x_{i,CO_2}^{\delta}$.

Solving this problem gives the following optimal resource input allocation:

$$\begin{cases} x_{i,capital}^{*} = \left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\alpha-1}} \cdot \left\{\sum_{i=1}^{113}\left[\left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\alpha-1}}\right]\right\}^{-1} \cdot \sum_{i=1}^{113} x_{i,capital} \\ x_{i,land}^{*} = \left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\beta-1}} \cdot \left\{\sum_{i=1}^{113}\left[\left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\beta-1}}\right]\right\}^{-1} \cdot \sum_{i=1}^{113} x_{i,land} \\ x_{i,labor}^{*} = \left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\gamma-1}} \cdot \left\{\sum_{i=1}^{113}\left[\left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\gamma-1}}\right]\right\}^{-1} \cdot \sum_{i=1}^{113} x_{i,labor} \\ x_{i,CO_2}^{*} = \left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\delta-1}} \cdot \left\{\sum_{i=1}^{113}\left[\left(\frac{\prod_{i=1}^{113} TE_i}{TE_i}\right)^{\frac{1}{\delta-1}}\right]\right\}^{-1} \cdot \sum_{i=1}^{113} x_{i,CO_2} \end{cases}$$

As a result, $Y_C = 284{,}875{,}488{,}910$. Following (9), we infer the reallocative efficiency of the group of the group $RE_{group} = \frac{Y_A}{Y_C} = 1.15$.

Scenario 4: Improvement of technical efficiency and feasible reallocation of inputs

If technical efficiency can increase to unity and inputs can be freely reallocated, the optimal resource input allocation can be reduced to (see (10)):

$$\begin{cases} x^*_{i,capital} = \frac{\sum_{i=1}^{113} x_{i,capital}}{113} \\ x^*_{i,land} = \frac{\sum_{i=1}^{113} x_{i,land}}{113} \\ x^*_{i,labor} = \frac{\sum_{i=1}^{113} x_{i,labor}}{113} \\ x^*_{i,CO_2} = \frac{\sum_{i=1}^{113} x_{i,CO_2}}{113} \end{cases}$$

This would yield a maximized output at the group level of $Y_D = 351{,}168{,}764{,}017$. According to (11), the reallocative technical efficiency $RTE_{group} = \frac{Y_A}{Y_D} = 1.42$.

5. Concluding Summary

This paper studies the relationship between European agricultural production, on the one hand, and capital, land area, labor, and GHG emission, on the other hand. Our research investigates this link for the first time from the perspective of the individual farm level to the group level and allows for reallocation possibilities of inputs between farms. It is shown that even if the technical efficiency of the farms remains the same, the output may increase by 15% in case of perfect reallocation possibilities of inputs between farms. If all farms move to their production frontier, the group output may increase by 38% in case of no reallocation possibilities of inputs between farms, and even by 42% in case of perfect reallocation possibilities of inputs between farms.

6. Recommendations for Future Research

In this paper, we constructed and applied several rather basic group efficiency measures. We see several key challenges for future research. Specifically, we suggest addressing the issue of scale, reallocation costs, and differing farming systems.

Scale

It is very likely that altering the number of considered farms changes the reallocation scheme and the according output gains. However, in which way and to what extent this happens has never been studied so far (Nesterenko and Zelenyuk, 2007). Therefore, one should respectively theoretically investigate and practically validate (by means of for example the comparison of EU-15 and EU-27 results) this scale issue.

Reallocation costs

Although output gains from reallocation at the group level are an interesting feature, this might result in extra transfer costs. In particular geographical distances may play an essential role in light of decision making (Nesterenko and Zelenyuk, 2007). The study of the trade-off between output gains and reallocation costs is consequently very important.

Differing farming systems

The baseline model presumes that there is only one production frontier for all farms considered. However, it might be useful to differentiate between conventional and organic farms, and between mixed and specialized farms.

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