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Population pressure and agricultural technological change¹

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Summary

Population Per Arable Land (PPAL) is introduced as a new explanatory variable in agricultural technological change. It is shown how incorporation of PPAL into the neo-classical production function model with a time shift variable encompasses both Boserup's hypothesis of technological change through population pressure and the induced innovation hypothesis of Ruttan and Hayami. The model is estimated on a pooled time series of 90 countries in Europe, Asia and Africa, and the PPAL coefficient is shown to be significantly positive. It can therefore be concluded that in these countries, which have not experienced the abrupt changes due to large immigrations, output changes substantially with increasing population pressure, all other inputs kept constant. It follows that farmers change their technology according to PPAL, in order to adjust their production to a growing population, facing a limited amount of arable land to take into production. This has important implications for agricultural research, which intends to develop the appropriate technology for the regions they cover. PPAL gives an important indicator as to what kind of technology is likely to be demanded and adopted by farmers. PPAL, however, cannot fully replace time as a shift variable in the production function. Time has an independent positive effect on technology, indicating that some technological innovations are transferable independent from PPAL.

1. Introduction

One of the fundamental questions in rural development is what makes farmers change their technology. If we believe that the development of agriculture is a key element in economic development, then the study of agricultural technological change should be a central part of development economics as well.

Working in rural development in Thailand, Togo and Mali, I noticed that two major factors made farmers interested in changing their technology: shortage of arable land and the demand for their products outside their extended family. Since demand is positively related to the population size we might combine these factors into one parameter of population pressure, expressed in Population Per Arable

¹ De Groot H. 1999. "Population Pressure and Agricultural Technological Change". *Quarterly Journal of International Agriculture* 38(1999), No. 3: 185-202.

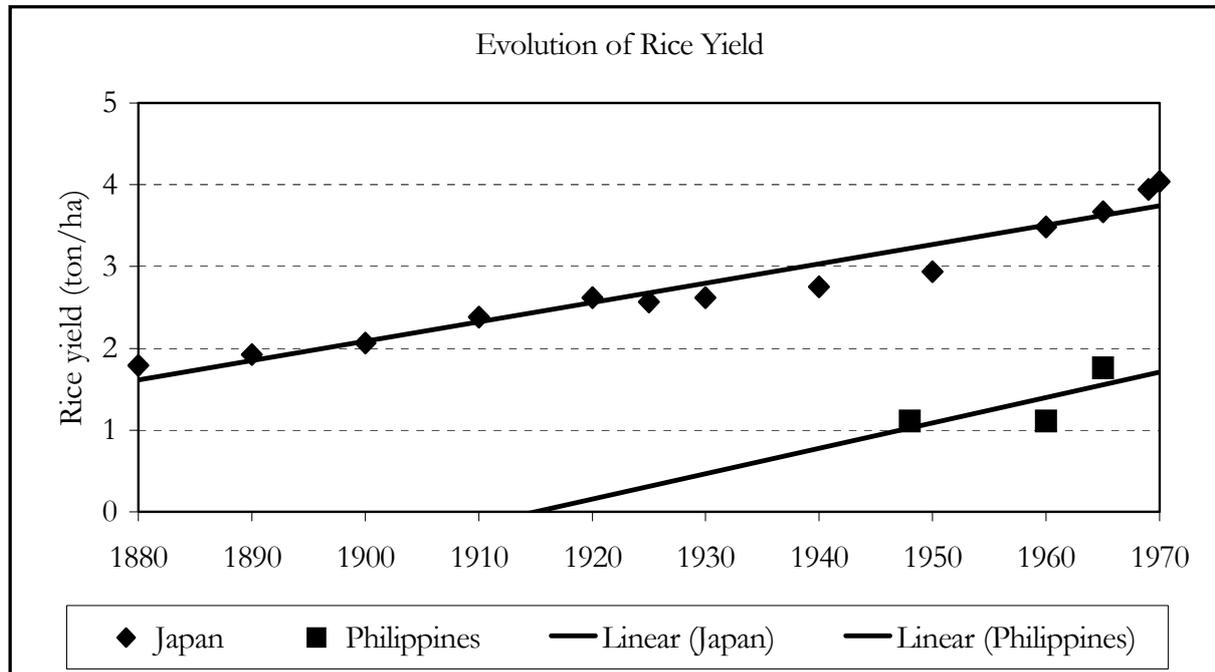
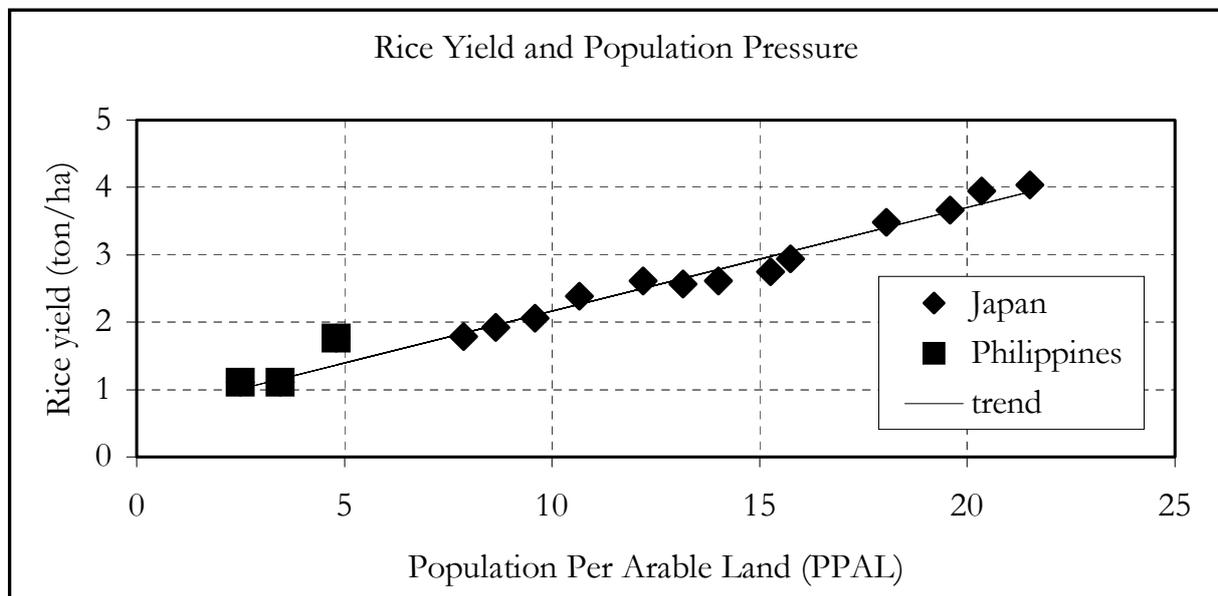
Land (PPAL). This parameter is very attractive because it is easily calculated and, as I will show later, most countries go through a monotonically increasing evolution of PPAL, which allows for comparisons over time and across countries.

The purpose of this paper is to explore the possibilities of using PPAL as a parameter in explaining agricultural technological change. A theoretical model will be developed and shown to encompass other approaches in the literature. A production function will then be estimated and the effect of PPAL tested. It will be shown that PPAL has an important impact on the evolution of agricultural technology, and could be very useful in explaining differences between countries and changes over time.

2. Concepts and hypotheses

Ester BOSERUP (1965) postulated in her classic work that population pressure causes farmers to invent or adopt new technology. She defined population pressure as population per area, classified countries in groups according to this pressure and compared the agricultural technology between groups. In a later work BOSERUP (1981) refined her definition by excluding desert, arctic and steep mountainous areas. She shows how countries with high population densities have a more intensive agricultural technology. This hypothesis is supported with more detailed evidence by authors like PINGALI, BIGOR and BINSWANGER (1987) and TIMMER (1988). In short, the hypothesis states that farmers will adapt to a higher population pressure by changing their technology from extensive systems such as hunting and gathering or forest fallow, towards more intensive systems by shortening and eventually eliminating fallow. This elimination of fallow is compensated for by incorporating animal husbandry and multiple cropping. The hypothesis has, to my knowledge, not yet been formally tested in a neoclassical economic framework, e.g. by including population pressure as a dependent variable in a production function or similar analysis.

HAYAMI, RUTTAN and SOUTHWORTH (1979) for example compare the evolution of rice yields in Japan and the Philippines. They plot the yields over time resulting in two parallel, upward sloping lines (Figure 1). This graph implies that different countries go through the same evolution at different times, but offers no explanation as to why the yields increase or why they increase at the same rate in different countries. If the same yields are plotted against PPAL then the two lines merge (Figure 2), suggesting that this variant of BOSERUP's hypothesis could be an important explanatory variable in models of agricultural development.

Figure 1. Evolution of rice yields in Japan and the Philippines, over time**Figure 2. Evolution of rice yields in Japan and the Philippines in relation to population pressure**

HAYAMI and RUTTAN (1985) accept the BOSERUP hypothesis to help explain the transition from traditional to modern agriculture, but do not let population pressure play a role in later development. They work out the induced innovation

hypothesis, which states that changing relative input/output prices induce innovation of technology towards a better use of the scarce factor.

Most authors on agricultural production use time as a variable to measure technological change, see e.g. CAPALBO and ANTLE (1988) for an overview. They usually estimate a production function

$$(1) \quad y = f(t, \mathbf{x})$$

where \mathbf{x} is a vector of inputs and t is time, and the rate of technological change is then defined as $\frac{\partial \ln y}{\partial t}$. The basic assumption is that technical change does not

require new inputs and that the production function maintains the same basic form over time, also referred to as disembodied technological change (CHAMBERS, 1988). A critique to this approach is that it does not offer any explanation of the technological change.

3. A new hypothesis

The hypothesized influence of PPAL on agricultural change can be formally stated as follows. In an economy with a closed agricultural sector, inelastic demand for its output, growing population and gradual socio-economical change, the technological change in agriculture is driven by the population pressure, expressed as Population Per Arable Land (PPAL). In the closed economy under consideration here, no trade of output or inputs is allowed. The closed economy requirement specifically excludes areas where large groups of farmers immigrated from areas with higher PPAL, as in the Americas and Australia. There is no reason to assume that immigrant farmers would abandon the technological level reached in their home country. It seems more logical that from the obtained level they would steer the technological evolution in a new direction, adapting to their new environment. Technological change can be seen as having a ratchet effect: Once obtained it is rarely lost. This does not mean that PPAL does not play a role here, but rather that its effect is structurally different and probably more complicated than in areas without such drastic immigration.

The hypothesis can be tested on a production function that allows for a shift of technology influenced by PPAL. To compare the influence of PPAL to that of time both factors have to be included. The general form of the model becomes:

$$(2) \quad y = f(\text{PPAL}, t, \mathbf{x})$$

where y = agricultural output, t = time, \mathbf{x} = inputs

Arguments can be made to use the lagged values of PPAL or changes in PPAL as explanatory variables. However, changes in PALL can be captured by its logarithm. Moreover, they are gradual so lagged values do not add much information.

4. Discussion of the model

PPAL is not only a convenient and easy to calculate measure of population pressure, it also forms a link between alternative approaches. In this section I will show that PPAL is an empirical improvement over BOSERUP's population density parameter, that under certain assumptions PPAL can be seen as a first order approximation to the input-output price ratio of the induced innovation hypothesis, and that it offers an important extension to the neo-classical approach.

PPAL is not very different from the population pressure on total area as used by BOSERUP. In certain applications BOSERUP (1981) excluded desert and arctic areas from the analysis. Non-arable land might have an impact on technological change through hunting and grazing on communal lands, but a developing country's agriculture typically evolves from those activities to crop production, which makes PPAL a more suitable parameter for population pressure.

In a closed agricultural economy, evolving gradually over time and without migration, the major input constraint is land. According to the induced innovation hypothesis the increased price of land w_r relative to the price of output p will induce innovation towards land saving technology. This price ratio w_r/p is closely related to PPAL by the following theorem.

THEOREM: *In a closed economy with an agricultural production sector and consumers with a linear expenditure function PPAL is related to the ratio w_r/p by the formula (3)*

$$(3) \quad \frac{w_r}{p} = \text{PPAL} \varepsilon_r \left[\gamma + \frac{\delta}{p} (M - \sum_j p_j \gamma_j) \right]$$

where w_r = rent

p = price of food, p_j = price of other goods

ε_r = output elasticity of land

m = income

γ = food requirement per person

γ_j = minimal needs of other goods j

δ = demand elasticity for food

PROOF: *see Appendix*

In order to appreciate this theorem we have to specify ε_r . In a second order approximation the production technology can be described by a translog production function where the output elasticities have the general form

$$\varepsilon_i = \alpha_i + \sum_j \alpha_{ij} \ln(x_j)$$

and the relationship becomes

$$(4) \quad \text{PPAL} = \frac{w_r}{p} [\alpha_r + \sum_j \alpha_{rj} \ln(x_j)] \left[\gamma + \frac{\delta}{p} (m - \sum_j p_j \gamma_j) \right]^{-1}$$

In a first order approximation of the technology (Cobb-Douglas production function) the output elasticity ε_i is held constant. For an agricultural product with perfectly inelastic demand, $\varepsilon=0$ and

$$(5) \quad w_r/p = \text{PPAL} \times \text{Constant}$$

or the input/output price ratio is directly related to PPAL. Note that the functional form of the food demand is not relevant as long as demand is perfectly inelastic.

It follows from (5) that *PPAL* can be seen as a first order approximation to the input/output price ratio. The advantage of PPAL over price ratios is clear: figures are readily available, cross-sectional data as well as time series, and no adjustments have to be made for different currencies and inflation. Because PPAL can be easily calculated it allows the inclusion in the analysis of countries with little or no developed land market such as most of sub-saharan Africa.

Agriculture includes animal husbandry and forestry, but the products of these sectors do not typically exhibit the inelastic demand necessary for the above theory. Therefore, only land in crop production is considered here in the variable *T*. To allow for extensive agricultural systems fallow has to be included, which makes cultivated land approximately equal to arable land.

The standard approach to measure technological change in the neo-classical production literature is to include a shift variable *t* for time in the production function $y = f(t, \mathbf{x})$. This time variable captures all unknown factors. Following the above PPAL-hypothesis different countries would be in different stages of PPAL at a given *t*. Therefore, PPAL has to be introduced in the production function, while *t* can remain to capture the state of technology in the world. Thus, the PPAL model is a production function with shift variables time and PPAL given by (2).

This approach can be regarded as a synthesis of the previous models: It allows for population pressure to influence technological change as in the BOSERUP model, it can be seen as a first order approximation to input-output price ratios as in the

induced innovation model, and it allows for a change of technology over time as in the neoclassical model. Moreover, the PPAL model allows estimation of the meta-production function.

HAYAMI and RUTTAN (1985) describe the meta-production function as the envelope of short-term, constant-technology, neo-classical production functions. Their basic assumption is that this envelope approximates the innovation curve and therefore the long-run production function equal to all countries, which can thus be estimated directly on cross-country data. They acknowledge that the meta-production function shifts over time, but assume that this shift is not important for empirical estimation. Moreover, they hypothesize “that technical advance in agriculture occurs primarily as a result of new economic opportunities created by developments in the nonagricultural sector” (HAYAMI and RUTTAN, 1985: 137).

The PPAL-hypothesis, in contrast, assumes that shifts in the meta-production function are important and come from within the agricultural sector, or rather the relationship between the output demand in the whole economy with respect to the input constraint in the agricultural sector, expressed in the variable Population Per Arable Land. Therefore the PPAL model can be estimated on pooled time series data of different countries, hereby assuming that these countries go through the same changes of technology according to population pressure per arable land.

Two specifications will be used in the empirical analysis:

- the Cobb-Douglas production function, linear in the logarithms and a general first order approximation of any production function (CHAMBERS, 1988)
- the translog production function, quadratic in the logarithms and a general second order approximation.

With these specifications the testable PALL-hypothesis becomes:

$$(6) \quad \frac{\partial \ln y(t, PPAL, x)}{\partial \ln PPAL} > 0$$

or PPAL has a positive effect on production with other inputs kept constant, implying a technological change. A related hypothesis is

$$(7) \quad \frac{\partial \ln y(t, PPAL, x)}{\partial t} = 0$$

or if population pressure has been taken into account time has no more effect on agricultural technology. Rejecting the last hypothesis, however, does not imply rejecting the PPAL hypothesis.

5. Data

The inputs to be included in the model are those published by the Food and Agriculture Organization, FAO (1980-1989): fertilizers (total in metric ton, $N+P^2O_5+K$), agricultural labor, arable land (land in temporary crop production, temporary meadow or fallow, in 1000 ha) and tractors (all types combined).

The FAO does not publish an aggregate variable for agricultural output, apart from indices per country. Therefore, Added Value in Agriculture (AVA), published by the World Bank (1990), was chosen as output variable. For the present analysis AVA is converted to constant 1980 dollars using World Bank indices.

PPAL is expressed as total population per hectare of arable land. Population data are published by the WORLD BANK (1990). To allow for an evolution over time the data for 1978 to 1988 were included. Population is increasing in almost all countries; notable exceptions are a few highly industrialized countries (WORLD BANK, 1990). At the same time arable land has increased only slightly in most countries, again with the exception of some highly industrialized countries where urbanization is appropriating some arable land (FAO, 1980-1989). As a result PPAL increases monotonically over time, with very few exceptions.

As explained above the Americas and Australia would not fall under the PPAL-hypothesis. Even though the major immigrations took place before the time period under study these regions combine a low PPAL with a high level of technology. Therefore, only countries in Europe, Asia and Africa were included in the data set. Complete data were available for about 90 countries. Countries are separated into six regions according to the FAO: North Africa, Sub-Saharan Africa, Middle East, Far East, Western Europe and Eastern Europe.

6. Empirical analysis

The model is estimated on pooled cross-country and time series data, hereby taking maximum advantage of the availability of PPAL. Since the error terms of an Ordinary Least Squares estimation of a specific country for different times are unlikely to be independent, a pooled time series approach will be used. The assumptions, to be tested first, are:

- a first order auto-correlation of the error term within countries, between consecutive years
- heteroskedasticity between countries

The model will then be estimated by Feasible Generalized Least Squares.

Since the data are pooled time series, adjustments have to be made for auto-correlation among countries and heteroskedasticity between countries. The basic assumption is that all countries face the same production function, except for the intercept, which is allowed to shift by region to account for climatological differences. All variables are linear in the logarithms except for the variable time, which is strictly linear. The error term is assumed to follow a first order autoregressive process. The variance of the adjusted error term is assumed to be constant within, but varying between countries.

The formal model, based on a Cobb-Douglas production function after Kmenta (1971), is as follows:

$$(8) \quad \ln(y_{it}) = \sum_j \delta_j d_j + \alpha_{tt} + \alpha_p \ln(\text{PPAL}_{it}) + \sum_k \alpha_k \ln(x_{kit}) + \varepsilon_{it}$$

$$\varepsilon_{it} = \rho \varepsilon_{i,t-1} + u_{it} \quad (\text{auto-correlation})$$

$$u_{it} \sim N(0, \sigma_i^2) \quad (\text{heteroskedasticity})$$

$$E(u_{i,t-1} \varepsilon_{jt}) = 0 \quad \forall i, j, t$$

$$\varepsilon_{i0} \sim N\left(0, \frac{\sigma_i^2}{1 - \rho^2}\right)$$

where: y_{it} = agricultural output in country i at time t
 x_{kit} = agricultural input k in country i at time t
 $t = 1 \dots 11$ where $1=1978$, $11=1988$
 $i = 90$ countries from Europe, Asia and Africa
 $k = 1, 2, 3, 4$: fertilizer, labor, land, tractors
 d_j = regional dummy variables, $j = 1$ (N.Africa), 2 (Sub-Saharan Africa),
 3 (Middle-East), 4 (Far-East), 5 (E.Europe) and 6 (W.Europe)

The parameters are estimated by Feasible Generalized Least Squares, in three steps:

i) OLS estimation of (8), which allows to estimate from the error terms

$$\hat{\rho} = \frac{\sum_i \sum_t e_{it} e_{i,t-1}}{\sum_i \sum_t e_{i,t-1}^2} \quad (i = 1, 2, \dots, N; t = 2, 3, \dots, T) = 0.90$$

ii) OLS estimation of (8) on the variables adjusted for auto-correlation:

$$Z_{it}^* = Z_{it} - \rho Z_{i,t-1} \quad \text{where } Z = \text{all variables } y, x, \text{PPAL, } d$$

which allows to estimate for each country i the variance of the error term

$$s_{ui}^2 = \frac{1}{T - K - 1} \sum_{t=2}^T \hat{u}_{it}^{*2}$$

- iii) Weighted Least Squares estimation of (8) on the adjusted variables, with weight = s_{ui}

The error terms were tested for auto-correlation after the first step, with an adjusted Durbin-Watson test, calculated as:

$$d' = \frac{\sum_i \sum_t (e_{it} - e_{i,t-1})^2}{\sum_i \sum_t e_{i,t-1}^2} \quad (i = 1, 2, \dots, N; t = 2, 3, \dots, T)$$

The calculated value is $d' = 0.0564$, for $N \times (T-1) = 642$. For $k=11$, $T=200$ the critical values are $d_L^* = 1.665$, $d_U^* = 1.874$. Since $d' < d_L^*$ the hypothesis that the error terms are positively correlated can not be rejected.

The estimated parameters and standard errors are given in Table 1. A full model was estimated with results shown in the first column (a), as well as three shorter models to follow the effect of different specifications: without time (b), without PPAL (c) and without both time and PPAL (d). The estimated coefficients on the inputs are all between zero and one, the standard errors are relatively small and that the size elasticity is 0.93, with a standard error of 0.022. Thus, the estimated parameters are of dimensions acceptable for a Cobb-Douglas production function, according to production theory.

The estimated coefficient for $\ln PPAL$ is 0.61 and significantly larger than zero at the 5% significance level (t-value=14.776). Thus the hypothesis $\frac{\partial \ln y}{\partial \ln PPAL} > 0$ cannot be rejected. If Population Per Arable Land increases by 1%, the production increases by 0.61%, keeping all inputs constant. This means that PPAL influences positively the productivity of the inputs, implying that a shift in technology takes place with increasing population pressure. This provides strong evidence that PPAL is an important factor in agricultural development.

Table 1. Estimated parameters for the Cobb-Douglas production function, corrected for auto-correlation ($\rho = 0.90$) and heteroskedasticity, dependent variable is $\ln(\text{added value in agriculture})$, standard errors in parentheses.

Error! Bookmark not defined.	full model	shorter models			
	(a)	(b)	(c)	(d)	
Intercept	0.98 (0.05) **	0.95 (0.05) ***	1.71 (0.02) ***	1.71 (0.05) ***	
Sub-Saharan Africa	-1.22 (0.12) **	-1.12 (0.12) ***	-1.74 (0.14) ***	-1.57 (0.14) ***	
East-Europe	-0.67 (0.25) **	-0.46 (0.25)	-1.35 (0.29) ***	-0.99 (0.28) ***	
Far-East	-0.57 (0.11) **	-0.53 (0.11) ***	-0.39 (0.13) **	-0.30 (0.13) *	
Mid-East	-0.66 (0.14) **	-0.59 (0.14) ***	-0.71 (0.16) ***	-0.57 (0.16) ***	
North-Africa	-0.82 (0.12) **	-0.73 (0.12) ***	-1.09 (0.13) ***	-0.94 (0.13) ***	
time (1978=1)	0.01 (0.00) *		0.02 (0.00) ***		
$\ln(\text{PPAL})$	0.61 (0.04) **	0.64 (0.04) ***			
$\ln(\text{fertilizer})$	0.03 (0.01) **	0.04 (0.01) ***	0.06 (0.01) ***	0.06 (0.01) ***	
$\ln(\text{land})$	0.68 (0.04) **	0.70 (0.04) ***	0.11 (0.02) ***	0.11 (0.02) ***	
$\ln(\text{labor})$	0.16 (0.03)	0.15 (0.03) ***	0.43 (0.02) ***	0.44 (0.02) ***	
$\ln(\text{tractors})$	0.06 (0.01)	0.06 (0.01) ***	0.10 (0.02) ***	0.11 (0.02) ***	
R^2	0.87	0.87	0.83	0.82	
N	681	681	671	681	
Root MSE	0.21	0.21	0.24	0.24	

***, **, *: significant at the 0.1%, 1% and 5% level

The parameter for time is significantly larger than 0 at the 5% level so the hypothesis $\partial \ln y / \partial t = 0$ has to be rejected (t -value=2.97). The coefficient for time is 0.01, meaning that every year the productivity increases by 1% if all other factors stay constant.

It is clear that PPAL can not fully replace time as a shift variable for technology. There seem to be factors that improve technology over time across countries, regardless of the population density. Since the relationship between PPAL and input/output ratios is only constant if the output elasticity for land and the demand elasticity for food is constant, it could be that the increase of PPAL over time does not quite reflect the changing price ratios.

A more appealing explanation, however, is that some technological improvements are easily disseminated across borders and adopted independent of PPAL. Say for example that one country develops a technological improvement in inputs, such that its marginal productivity increases more than its marginal cost. An example would be the development of a new insecticide. If there are no additional costs or externalities involved, other countries would replace their old input with this new one. Chemical technology is easily disseminated.

The influence of the parameter time and PPAL can be examined by estimating shorter models without the respective variables. The F -tests for the short models reflect a significant difference; thus the short models are misspecifications (the calculated F -values are respectively 8.8, 218.3 and 126.9).

The effect of dropping time is minimal, as can be seen by comparing columns (a) and (b) in Table 1. Although statistically a misspecification, dropping time does not change the estimated coefficients in a meaningful way. Dropping PPAL on the other hand causes major changes as can be seen by comparing column (a) and column (c). Thus, estimation of a neoclassical model $y(t, \mathbf{x})$ on cross-country data is a misspecification that results in major errors in coefficient estimates.

Western Europe is the dummy variable dropped in the estimation, so the intercept can be seen as the intercept for Western Europe. The coefficients of the other regions are deviations from this intercept.

A second specification, the translog production function, was also estimated, since it can be regarded as a general second order approximation (CHAMBERS, 1988). The results, however, were disappointing. The elasticities of this specification are linear functions of the estimated coefficients, and their variance is a quadratic function of the variance-covariance of the coefficients. Since many of the coefficients show large standard errors, the relevant elasticities were not significantly different from zero.

7. Conclusions and implications

The PPAL model $y=f(t,PPAL,\mathbf{x})$ is a convenient way to study the effect of population pressure on technological change in agriculture across countries. The coefficients of the Cobb-Douglas production function are all different from zero at the 1% significance level, while the translog specification has many non-significant parameters and larger standard errors for the test statistics of the hypotheses. Therefore, the Cobb-Douglas production function is preferred.

It can be concluded that in Europe, Asia and Africa output changes substantially with increasing population pressure, keeping all inputs constant. It follows that farmers change their technology according to population per arable land, in order to adjust their production to a growing population, facing a limited amount of arable land to take into production. PPAL, however, cannot fully replace time as a shift variable in the production function. Time has a positive effect on technology apart from increasing population pressure. Hence some factors in technology are transferable independent from PPAL.

In general, countries keep up with increased population pressure by increased food production. Facing a limited area of arable land, this is achieved by increasing inputs and improving agricultural technology. Therefore, a growing population is not a burden on agricultural development but an incentive. This does not mean, however, that occasionally population growth can not outpace the farmers' ability to adjust.

Good development policy, be it from governments or development agencies, should take into account this natural adjustment and create the conditions to facilitate it. Given the effect of PPAL on technological change, estimations of population growth can be used to predict the speed of technological change, and therefore the demand of farmers for new technology or inputs.

Policy implications are especially important for agricultural research stations, infrastructure and education. More precisely, agricultural research stations can be organized to be slightly ahead of the expected demand for technology from farmers and therefore fast to respond. Demand for infrastructure (roads, bridges, markets, etc.) can equally be foreseen and planned for. Similarly, agricultural education and extension should follow the predictable demand.

Problems arise when policies do not run parallel to the PPAL-induced technological change. Imports of advanced technology far ahead of the demand are not uncommon. On the other hand, farmers often face problems in accessing the technology they demand, as with government monopolies or import restrictions on inputs.

Finally, a policy of importing cheap or subsidized food will decrease the effect of PPAL by artificially reducing the demand for local food products. It decreases the incentive for technological change and will impede agricultural development on the long run.

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Acknowledgements

The author would like to thank Michael Carter, Patti Champ, Jeff Cochrane, Kimberley Smith, James Walker, Tim Wojan, Lydia Zepeda and Jürgen Langewald for their help and support.

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APPENDIX: PROOF OF THE THEOREM

THEOREM: *In a closed economy with an agricultural production sector and consumers with a linear expenditure function PPAL is related to the ratio w_r/p by the formula*

$$\frac{w_r}{p} = \text{PPAL} \varepsilon_r \left[\gamma + \frac{\delta}{p} (M - \sum_j p_j \gamma_j) \right]$$

PROOF:

Assume all farms face the same production function:

$$y = f(\mathbf{x}) \quad \text{where } y = \text{agricultural output,} \\ \mathbf{x} = \text{input bundle}$$

Assume farmers are profit maximizers, then

$$p \frac{\partial y}{\partial \mathbf{x}} = \mathbf{w} \quad \text{where } p = \text{output price, } \mathbf{w} = \text{input prices}$$

and $p \frac{y}{\mathbf{x}} \boldsymbol{\varepsilon} = \mathbf{w}$ where $\boldsymbol{\varepsilon}$ = elasticities

Transformation of this first order condition for land gives the farm's supply

$$y = w_r x_r / p \varepsilon_r \quad \text{where } r \text{ stands for land}$$

If there are N_f identical farms then the aggregate agricultural supply is given by:

$$Q_s = \frac{N_f x_r w_r}{\varepsilon_r p}$$

If the utility function is a linear expenditure function the demand for the agricultural good z is

$$z^D = \gamma + \delta (m - \sum_j p_j \gamma_j) / p \quad \text{where } p_j = \text{price of other goods } j \\ m = \text{income per person} \\ \gamma = \text{food requirement per person} \\ \delta = \text{demand elasticity for food}$$

If all consumers are identical the aggregate demand becomes

$$Q^D = N [\gamma + \delta (m - \sum_j p_j \gamma_j) / p] \quad \text{where } N = \text{population}$$

In equilibrium supply equals demand or $Q^s = Q^D$

$$\frac{N_f x_r w_r}{p \varepsilon_r} = N \left[\gamma + \frac{\delta}{p} (m - \sum_j p_j \gamma_j) \right]$$

$$\frac{w_r}{p} = \frac{N[\gamma + \frac{\delta}{p}(m - \sum_j p_j \gamma_j)] \varepsilon_r}{N_f x_r} = \frac{N}{T} \varepsilon_r [\gamma + \frac{\delta}{p}(m - \sum_j p_j \gamma_j)]$$

where $T =$ cultivated land

Therefore, when there is no idle land, $T =$ arable land and

$$\frac{w_r}{p} = PPAL \varepsilon_r [\gamma + \frac{\delta}{p}(m - \sum_j p_j \gamma_j)]$$

Q.E.D