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Agricultural intensification in Ghana: Evaluating the optimist's case for a Green Revolution

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ABSTRACT

While there are valid reasons for a renewed interest in adapting the lessons of the Asian Green Revolution to the African setting, research must go further in identifying the main, and potentially unique, drivers of agricultural intensification within and across African countries. In this study we look at the case of Ghana to identify whether fast population growth and the remarkable agricultural performance the country has enjoyed in recent years have resulted in favorable conditions for the adoption of Asian-style Green Revolution technologies. Through descriptive analysis combined with empirical assessment of the economic efficiency of agriculture in different production systems and agroecologies we are able assess the relevance of Green Revolution technologies for agricultural production in Ghana. In particular, we analyze whether fertilizer use in Ghana is associated with high population density and intensive cereal production and whether land-intensive innovations are associated with more efficient production practices. Overall, we do not find evidence of Asian-style Green Revolution agricultural intensification in Ghana; in fact, we find no correlation between population density and input intensity. We also find that labor costs still play a major role in Ghanaian agricultural development in limiting the adoption of labor-intensive technologies even in relatively high population density areas.

Introduction

During the 1960s and 1970s, Asian and Latin American countries experienced yield increases and accelerated agricultural output growth due to the adoption of high yielding varieties of wheat, rice, and maize combined with intensive use of inputs such as fertilizer and irrigation. However, the transformation of agriculture brought to these regions by the Green Revolution did not reach Africa. Following independence in the late 1960s and 1970s, African governments and donors alike attempted to increase agricultural production by developing policies and programs inspired by the Asian Green Revolution (Crawford et al., 2003). These policies and programs led to heavy reliance on input subsidies, government-provided services (marketing, infrastructure, extension, research), and the establishment of input and commodity marketing parastatals. However, in the African setting, these policies produced little effect in terms of increasing use of chemical fertilizer or high yielding varieties.

It is now clear that, in part, the failure to increase yields and the use of modern inputs in the past were due to conditions in Africa that were quite different at that time from those in Asia. For example, the demand for chemical inputs was low because land was relatively abundant and farmers had little incentive to use cultivated land more intensively or to save on land costs (Binswanger and Pingali, 1988). In contrast with Asia, most crop area in Africa is unfertilized and hoe-cultivated; and little animal ploughing is practiced. Traditionally, African farmers have alternated crops with long fallows (shifting cultivation) and practice intercropping as the primary method for reducing weeds and pests as compared with hand-weeding, manual pest control, and the employment of agrochemicals, as is common in Asia (Lipton, 2012). In this context, output growth between 1960 and 2000 has been achieved mainly by expansion of cultivated area and more intensive use of owned land, i.e., reduction in fallow periods to increase the area under cultivation in a given year, with little or no improvement in yields (Evenson and Gollin, 2003).

In addition, differences in labor availability and agroecology resulted in crop mixes in sub-Saharan Africa (SSA) that differed significantly from those in Asia. In addition, African smallholders have long produced higher proportions of non-cereal staples (for example, cassava and plantain) and higher proportions of food

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crops that are consumed in the household or sold in local markets rather than marketed to the city. Because of this, improvements in rice, wheat, and maize that largely addressed the main food security concerns in Asia were not appropriate for African regions with diverse cropping systems where many non-cereal crops were central to food security. Even where major cereals were grown in Africa, suitable varieties for those agroecologies only became available in the 1980s, due to research specially targeted to African conditions (Pingali, 2012).

In this unfavorable context for the type of policies applied in Asia to promote agricultural development, the government-led approach was financially unsustainable and collapsed in macroeconomic crises in many African countries. Consequently, development strategies shifted in the opposite direction—away from government intervention and also away from agriculture-led development. Structural adjustment programs (SAPs) were implemented in the 1980s with a focus on private sector development, putting an end to the Green Revolution-inspired government-led process of agricultural transformation. However, expectations that the private sector would fill in the gaps left by retreating governments were not fulfilled (Dorward et al., 1998; Jayne et al., 2002), and access to and use of inputs, particularly fertilizers, declined (Gordon, 2000; Bumb and Baanante, 1996).

More recently, the policy pendulum has swung back. At present, direct state support for technical innovation and African agricultural productivity are again high on many policy and research agendas. With these priorities comes renewed interest in the lessons of the Asian Green Revolution as well as renewed government support for agriculture, input promotion programs, and subsidies (Diao et al., 2008; Morris et al., 2007; Reardon et al., 1999). As in the past, in most cases, the focus of these policies and programs remains on a land scarce-labor abundant model in which technology supply, intensive input use, and addressing natural resource constraints are ready solutions (Cleaver and Donovan, 1995; Morris et al., 2007). If conditions in the past were admittedly so different from those in Asia, what has changed at present to justify a second look at the Asian Green Revolution as a possible model for agricultural development in Africa?

One possible answer to this question is given by Pingali (2012), who asserts that a confluence of factors has come together in recent years to generate renewed interest in agriculture and spur the early stages of the Green Revolution in Africa. According to Pingali (2012), the combination of continued food deficits, increasing reliance on food aid and food imports, soaring populations, growing land scarcity, rapidly growing urban demand, and an improved macro-economic environment in many African countries has reintroduced agriculture as an engine of growth in the policy agenda. Adding to this favorable environment for agriculture, new studies provide tangible evidence of the increasing availability of improved varieties of major food crops to farmers in Africa, increased food production in regions where adoption has occurred, and positive returns to research investment. The widespread adoption of improved maize, wheat, and rice varieties in Africa since the early 1990s is especially noteworthy (Maredia et al., 2000).

This renewed optimism about the possibility of an Asian-style Green Revolution taking root in Africa seems to be based on the assumption that rapid population growth on the continent will result in declining labor costs and growing land constraints, generating economic conditions similar to those in Asia. Under such reasoning, these conditions will lead to the adoption of labor-intensive technologies and greater fertilizer use, particularly in densely populated areas with relatively low labor costs and high returns to a more intensive use of land. Is this renewed optimism overlooking the structural and agroecological characteristics of African agriculture that have resulted in the failure of policies pushing land-saving technologies in the past?

We claim that assuming Africa is an appropriate setting for another Asian-style Green Revolution is misleading and could result in, yet again, a frustrated attempt to attain sustainable agricultural growth. As discussed by Woodhouse (2009) and despite rapid population growth, the performance of African agriculture is still largely limited by the high cost and low productivity of labor. Vast areas of agricultural land in many African countries are still under low population pressure. According to Binswanger and Pingali (1988), one-third of all SSA countries will still have extensive rural areas with low population densities in 2025 despite rapid population growth, and shifting cultivation will still be the most common system of farming in these countries.[1] Of the remaining two-thirds of SSA countries, most are naturally resource rich countries where labor costs could remain high even in areas of high population density as a result of structural characteristics that produce rapid urbanization even at low levels of agricultural intensification (Gollin et al., 2013). In other words, land and labor endowments across Africa are diverse (c.f. Headey and Jayne, 2014 and Chamberlin et al., 2014, this issue) and resource rich economies are structurally different from labor abundant economies; population growth will not necessarily transform resource rich African economies into labor-abundant, low labor cost economies.

Adding to structural economic differences, agroecological differences between Africa and Asia are important in explaining fertilizer use and intensification in cereal production, particularly in regions where production of non-cereal staples is significant. For instance, cassava production has expanded in Africa as a food security crop, replacing fallow. Generally, cassava can give reasonable yields in soils of low fertility and is thought to require less labor per unit of output than most other major staples; in fact, expansion of cassava production in Africa appears to be leading to greater labor productivity in the region (Hillocks, 2002). Increasing cassava production could be a profitable alternative to intensive cereal production when labor still imposes significant constraints to production expansion.

To begin addressing the questions and concerns raised above, we take Ghana as a case study. We first provide descriptive statistical analysis of the variation of outputs and inputs per hectare across various population densities and production systems. Unlike other studies in the existing literature that look at population density and agricultural intensification, we also introduce efficiency analysis to determine whether intensive "Green Revolution" technologies are relevant. By comparing the production practices of efficient and inefficient producers we gain a better understanding of the technological conditions of the most efficient producers and we are able to determine whether the use of fertilizer and chemical inputs is correlated with more efficient production practices. Evidence of strong correlation between population density and input intensification or between fertilizer use and economic efficiency in high population density areas would support the optimist's case for an Asian-style Green Revolution in Africa. Clearly, an absence of such evidence would not be sufficient for dismissal of this optimism; however, it should suggest the need for more in-depth analyses of the paths for technical change in agriculture and its linkages with the structural transformation of African economies.

Ghana is an interesting case because its rural population density today is much lower than that in labor-abundant African countries such as Rwanda, Malawi, Uganda, and Nigeria but much higher than that in land-abundant African countries such as Angola, Sudan, South Africa, and Mali. In addition, population density in Ghana today is low compared to that of Asian countries

[1] Jayne et al. (2014, this issue) show that, as of 2010, 70% of the rural population in SSA is clustered on 20% of the rural arable land, indicating that 80% of the rural arable land remains sparsely populated by the remaining 30% of the rural population.

during the Green Revolution but much higher than that of Latin American countries during the same period. Therefore, the relative limitations and contributions of land and labor to agricultural productivity growth in Ghana are not immediately clear. Ghana is also an interesting case because it exhibits the double condition of being a relatively populous country compared to the average population density in Africa while being a highly specialized exporter of natural resource commodities such as cocoa, minerals, and, more recently, oil.

We use cross-section data from the fifth round of the Ghana Living Standards Survey (GLSS5), a nationally representative survey of 8687 farm and non-farm households from 580 enumeration areas collected between September 2005 and September 2006 (GSS, 2008). Although definitive conclusions cannot be reached due to the limitations of our data and approach, we find no evidence that agricultural intensification in Ghana is following an Asian-style Green Revolution. Specifically, we find no correlation between population density and input intensity; further, we find that labor costs still play a major role in limiting the adoption of labor-intensive technologies even in densely populated areas.

The next section presents some of the main conceptual issues pertaining to our analysis. Section 'Methodology' discusses the methodology used to estimate household-level economic efficiency, as related to fertilizer use and cereal production. Section 'Characterization of agricultural production in Ghana' presents a brief characterization of agriculture in Ghana. Section 'Patterns of agricultural intensification' analyzes patterns of agricultural intensification by comparing intensity of input use and output per hectare at different population density levels, and Section 'Land- or labor-saving technologies?' analyzes the association between input use and share of different crops in total output and economic efficiency at the household level. Section 'Conclusions' concludes.

Conceptual framework

The importance of relative resource abundance as a determinant of technical change pathways has been part of the economics of technical change since the 1970s when Ruttan, Hayami, and Binswanger (Hayami and Ruttan, 1971, 1985; Binswanger and Ruttan, 1978) formulated a model of induced technical change in which the development and application of new technology is endogenous to the economy. According to this model, the direction of technical change in agriculture is induced by differences in relative resource endowments and factor prices. Because of the relatively high prices of less abundant resources, alternative agricultural technologies are developed to facilitate the substitution of relatively scarce (hence, expensive) with abundant (hence, cheap) factors.

More recently, Acemoglu (1998, 2002, 2007), contributing to what is today known as the directed technological change literature, provides a characterization of how the bias of technology will change in response to changes in factor supply. According to Acemoglu (2007), an increase in the supply of a factor always induces a change in technology biased toward that factor. For example, labor scarcity induces technological advances if available technology is strongly labor-saving while labor scarcity discourages technological advances if the technology is strongly labor-using or if wages increase above the competitive equilibrium (Acemoglu 2009).

Different agricultural innovations use factors of production differently and so demand for a particular innovation varies by region depending on the relative abundance and costs of factors. Binswanger (1986) classifies agricultural innovations according to how they use land, labor, and inputs as (a) yield increasing or (b) labor saving innovations.[2] Yield increasing innovations fall into three categories: (i) input-using innovations such as fertilizer and pesticides; (ii) stress-avoiding innovations based on genetic resistance or tolerance to pest, disease, or water stress; and (iii) husbandry techniques such as better land preparation, or intensive mechanical weeding. Labor-saving innovations include the use of machines, draft animals, implements and herbicides. According to Binswanger (1986), labor-saving innovations do not usually reduce area and have very little, if any, effect on yields. For these innovations to be adopted, the labor savings need to be larger than the extra machine or herbicide costs, and their value rises with rising wages. Therefore, the implications for technology adoption in land abundant regions are that farmers in these regions demand labor-saving innovations and crops that enable them to produce more food or a higher value of output per hour of labor employed.

Over the long-run, the most important factor contributing to land scarcity with respect to labor is population pressure. And this is the focus of Boserup (1965) and Ruthenberg (1980), who understood intensification as the process of relative changes in the availability of land, labor, and capital driven by population growth and by the higher returns to farming that arise with improvements in market infrastructure and farm gate price increases.

In Boserup's model, an agrarian community has a fixed territory and an array of discrete production techniques from which to choose: forest fallow, bush fallow, short fallow, annual cropping and multicropping. Each of these stages entails different cultivation techniques and the model implies a progression from less to more intensive cultivation. In this context, "intensification" implies that a greater proportion of available farmland is placed under cultivation in a given year, where the length of the average fallow period for land that has been used for production is shortened. Boserup (1965) argued that increasing population pressure provides the primary stimulus for innovation and intensification; core to her model is the notion that technological change is induced or impelled by a 'critical' population density.

Boserup's model has made a major contribution to the understanding of the process of agricultural intensification in non-industrial communities while representing a clear repudiation of Malthusian population pessimism. However, the model was not developed to account for the complexities of African agricultural transformation at the present time. One major limitation of the Boserupian model for this purpose is that it is based on an ideal closed economy and cannot account for the exogenous factors relevant in today's global economy, such as access to urban or foreign markets. Even in low-density areas, farmers facing a growing demand, arising largely from newly accessible markets, will want to produce more, which will increase demand for land and spur more intensive land use. An important difference between this market-driven growth model and the Boserupian population pressure-driven growth model is that, in the former, favorable market conditions could accelerate the incorporation of new land to production and accelerate intensification, introducing intensive use of chemical inputs with high yielding varieties even in low population density regions. Moreover, the density threshold at which there is significant demand for fertilizers can be quite low provided other favorable conditions exist (Goldman and Smith, 1995). The implications for Africa are clear. Natural resource rich countries on a market-driven intensification path will demand agricultural innovations with strong labor-saving components rather than the land-saving technologies that were promoted in Asia. Binswanger (1986) reminds us that in Thailand, a country that has traditionally had an open land frontier, remarkable

[2] Binswanger's (1986) classification also includes quality increasing innovations; however, we do not discuss these here.

agricultural growth has come from area expansion and that fertilizer use levels and adoption of high yielding varieties have been below that in other Asian countries.

Even if we accept that market-driven intensification in Africa could result in demand for labor-saving rather than land-saving innovations, we could still assume that labor supply in agriculture will continue to grow due to population pressure, reducing labor costs in land abundant countries and creating conditions for the adoption of labor intensive technologies at least in high density areas. In other words, labor-intensive technologies could still be promoted in natural resource rich countries if we focus on high population density areas where farms are small, incomes are low and where a high proportion of the rural poor live.

A first problem with this reasoning is pointed out by Goldman (1993) and Smith et al. (1994) who distinguish between population-driven intensification based on Boserupian responses to population pressure and market-driven intensification. According to Goldman (1993), constraints to innovation could also appear in very dense areas when there is little potential to increase farm sizes. If no land is available for expansion, the additional wealth that agricultural investment and new technology can generate is limited and non-agricultural activities may then be preferable to investment in agriculture. In other words, population pressure is not necessary, nor is it sufficient, to trigger innovation.

A second problem with this approach is that it seems to assume that high density areas in resource rich countries behave like closed Boserupian models where population pressure will increase labor supply and farmers will have no other option than to introduce land saving technologies to increase output. The problem with this reasoning is that it does not consider the fact that high labor costs appear to be a structural characteristic of resource rich economies as a consequence of a different agricultural transformation path when compared with that occurring in labor abundant economies. One of the explanations for this persistence of high labor costs most commonly found in the literature relates to Dutch Disease, a phenomenon that arises when a strong upswing in the world price of the export commodity leads to increased purchasing power and increased demand for urban goods, real appreciation of the local currency and an increase in the relative price of non-tradable goods. The result of these changes is a shift of labor, pulled by the more attractive returns in the export commodity and in the non-traded goods and services and a "push" of workers into urban areas.

Gollin et al. (2013) develop a model that formally explains urbanization without industrialization and the persistence of high labor costs despite rapid population growth in Africa. One of the implications of natural resource rents is that natural resource rich economies do not experience a stage of labor abundance with low labor costs in agriculture, as was observed in Asia. What is observed instead, as described by Gollin et al. (2013), is rapid urbanization resulting in "consumption cities" that are made up primarily of workers in non-tradable services, surrounded by rural areas with high population density. These high population density rural areas either produce semi-subsistence agriculture while diversifying into non-farm activities (services) or they specialize in high-value crops. In addition, interspersed with these high population density rural areas are vast areas of relatively low population density dedicated to the production of export crops and semi-commercial agriculture. Multiple cropping and intensive use of chemical fertilizer associated with cereal production could be an option in high population density areas if it can compete with production in low density areas, and if returns to family labor in this activity are higher than other farm and non-farm activities that seem to be more attractive for smallholders. For example, in many countries natural resources favor production of cassava and other non-cereal staples that give higher marginal returns to labor than does intensive cereal production. These developments stand in contrast to the Asian case of labor-abundant economies where labor shifts out of agriculture into industrial employment resulting in "production cities" that produce tradable goods (manufacturing).

Therefore, drawing on the above discussion, we approach the data with the following questions: Is fertilizer use in Ghana correlated with high population density and intensive cereal production? Are land-intensive, rather than labor-intensive, innovations correlated with more efficient production practices? If so, in which regions and production systems?

Methodology

A methodological contribution of this study is that it combines descriptive statistical analysis of the variation of outputs and inputs per hectare with efficiency analysis to determine the benefits one should expect from "Green Revolution" technologies across various population densities and agroecological environments. According to Binswanger (1986), these benefits are dependent on the relative scarcities of the factors that are saved by the technical change. Innovations that do not reduce input requirements per unit of output of those factors that are scarce or expensive will not be easily adopted and will have a low social value. In other words, a reduction in the unit costs of production is a necessary condition for any farmer to consider an innovation as profitable. If we consider efficient producers as those producing at the lowest costs per unit of output, then the greater the reduction in unit costs achieved by the use of Green Revolution technologies, the higher will be the demand for and the probability of adoption of these technologies. If this is the case, we expect to observe adoption particularly among efficient producers. Comparing production practices of efficient and inefficient producers at different population density levels allow us to determine whether the use of fertilizer and chemical inputs is correlated with more efficient production practices. In particular, evidence of intensive use of fertilizer by efficient producers in high population density regions would indicate that the use of that technology contributes to an efficient use of resources in that environment and would support the case for an Asian-style Green Revolution in Africa.

To perform efficiency analysis, we need an indicator that allows us to compare production-allocation decisions across households and to quantify deviations from "optimal" behavior (i.e., inefficiencies). A variety of standard techniques have been developed to model optimizing behavior. For instance, a number of empirical studies have investigated the extent and determinants of cost and profit efficiency in agriculture using stochastic frontiers and nonparametric frontier analysis (often referred to as data envelopment analysis or DEA).[3] A different nonparametric approach to the analysis of allocation efficiency originated from work by Hanoch and Rothschild (1972), Afriat (1972), Diewert and Parkan (1983) and Varian (1984). This 'revealed profitability' methodology merely needs information on quantities and prices, and essentially applies

[3] The stochastic frontier production model specifies a functional form and incorporates a composed error structure with a two-sided symmetric term and a one-sided component that reflects inefficiency, while the two-sided error captures the random effects outside the control of the production unit. Nonparametric frontier models are based on mathematical programming techniques and do not require the specification of a functional form; however, they also do not allow for random noise or measurement error and their efficiency scores are potentially sensitive to outliers. See Kumbhakar, Knox, and Lovell (2000) for a general introduction to stochastic frontier analysis of technical efficiency. For surveys of the use of stochastic frontiers and DEA see Greene (1997) and Cook and Seiford (2009), respectively. See Thiam et al. (2001) for an early survey of applications of stochastic frontier analysis to agriculture.

the theory of convex sets to such data rather than considering them through the lens of a pre-specified function.[4]

In general, the use of standard dual representations of the production structure requires the corresponding maintained hypothesis of cost minimization or profit maximization, subject to parametric market prices. When prices are available, allocative efficiency can be calculated using either frontier or 'revealed profitability' analysis. However, in the absence of complete price information, application of these methods becomes problematic. Even when reliable price information can be retrieved, such information frequently applies only to a subset of input and output commodities. Most significantly, according to Thiam et al. (2001), the validity of dual frontier models has been controversial for some time, as it has been shown that profit maximization based on market prices is inappropriate in the context of developing country agriculture. Given the existence of binding constraints on decision making, the producer's decision is often made with respect to shadow prices rather than observed market prices. Therefore, farmers' decisions are allocatively efficient with respect to market prices only when the market prices reflect the opportunity cost of inputs and outputs and the farmer does not make systematic mistakes in decision making. The divergence between shadow and observed prices can be interpreted as the result of imperfect markets, government interventions, and various restrictions (Barrett et al., 2008).

An approach that can be used to remedy some of the limitations of the allocative efficiency analysis exploits the close relation between the nonparametric 'revealed profitability' approach and DEA, providing a natural extension of the existing nonparametric framework as the solution for dealing with incomplete price information and farm level shadow prices when assessing the validity of the profit maximization hypothesis. In particular, the approach used in this study circumvents data limitations by taking advantage of an interpretation of economic efficiency in DEA as technical efficiency evaluated at the most favorable prices, following Cherchye and Van Puyenbroeck (2007). Based on this interpretation, we can estimate an upper bound for profit efficiency by using output, purchased inputs and levels of land, family labor, and assets, which are evaluated at their shadow prices, and by incorporating monetary cost or revenue data for a limited number of commodities (Cherchye and Post, 2010). To do so, we build on assumptions of monotone and convex sets as used in the 'revealed profitability' approach.

To show how the DEA measure can be interpreted as a profit efficiency measure, we start with the DEA efficiency measure introduced by Banker et al. (1984). For this we need to define the production possibilities of the firm, or the input–output combinations that are technologically feasible and among which the producer makes allocation choices:

$$T \equiv \{(x, y) \in R_{+}^{m+s} / x \text{ can produce } y\} \quad (1)$$

T is the production possibilities space (PPS) describing all the feasible netput (z) combinations. When dealing with the efficiency measure in DEA, we encounter problems of information about the technology defined by T. If T is not known, DEA uses the set of observed netputs (S) assuming that $S \subseteq T$. DEA efficiency is not estimated using the S set directly but the convex monotone hull (*CMH*) of the observed sample S instead. The general definition of the Debreu (1951)–Farrell (1957) (*DF*) input efficiency used in DEA analysis is as follows:

[4] Varian (1990) argues that what he calls conventional methods are lacking in two senses: first, they have an excess reliance on parametric forms, and second, they test for statistically significant violations of optimization rather than economically significant violations. According to Varian (1990) it is possible to test reasonably complex models of optimization behavior without parametric specification.

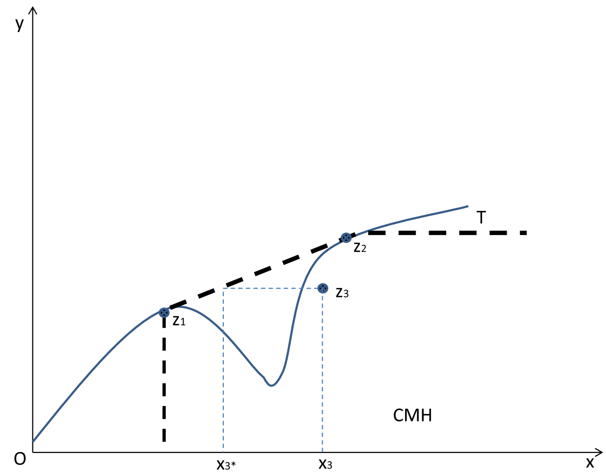

Fig. 1. Production and technical efficiency. *Source*: Adapted from Cherchye and Van Puyenbroeck (2007)

$$\theta^{DF}(y_i, x_j, CMH(S)) = min_{\lambda_z \in R^+, z \in (-x,y) \in S,} \left[\theta | \sum_{z \in S} \lambda_z y; \geqslant y_i; \sum_{z \in S} \lambda_z x \leqslant \theta x_j; \sum_{z \in S} \lambda_z = 1 \right] \quad (2)$$

In words, Eq. (2) says that the efficiency of using a particular combination of output y_i and input x_j is equal to the maximal equiproportional input contraction (for a given output) within the *CMH* of production space S. This can be seen graphically in Fig. 1.

The set S in Fig. 1 is a subset of the *CMH* and contains only three netput vectors $S = \{z_1, z_2, z_3\}$. In this particular case, the non-observed technology set T (i.e., the space under the solid line in Fig. 1) is not convex but it is included in the *CMH* defined to solve the efficiency problem (i.e., the space under the dashed line). Efficiency is measured for a particular point in S as the contraction of input to bring that point to the frontier of the CMH, which is defined by the most efficient points in production space. Efficiency of production unit z_3 in Fig. 1 is measured as the ratio $\theta_{z3} = Ox_3^*/Ox_3 \leqslant 1$, which takes a value between zero and one, inclusive, where any value less than one is inefficient. It is also clear from the picture that efficiency of production units z_1 and z_2 is $\theta_{z1} = \theta_{z2} = 1$, as both points are on the frontier of the *CMH* and hence are efficient production units. Given the particular combination of inputs that these two units use, it is not possible to produce more output than they currently produce, given the current technology.

According to Cherchye and Van Puyenbroeck (2007) one of the shortcomings of the DEA model is that it assumes monotone and convex production possibility sets, which are not necessarily characteristics of technologies and could be unrealistic assumptions in many practical situations. Cherchye and Van Puyenbroeck argue that DEA does not always agree with microeconomic theory as a tool for technical efficiency analysis (although it is conventionally employed for that purpose). Instead, they contend that the DEA approach is a well-founded tool for profit efficiency testing and measurement. Within this perspective, they extend the original Banker et al. (1984) model including monetary (cost or revenue) data for a limited number of commodities.

Starting from the same technology defined for the DEA efficiency measure problem, profit efficiency can be defined in this context as:

$$\pi^{Ep}(p, w, x_j, y_i) = \max_{-x_i, y_i \in S} \lfloor p_i(y - y_i) - w_j(x - x_j) \rfloor = 0 \quad (3)$$

If price information is available, this measure is straightforward and says that a particular combination of inputs x_j and outputs y_i is profit efficient if, given output prices p_i and input prices w_j, there is no other combination of y and x that results in $y > y_i$ and/or $x_j > x$.

The problem of measuring profit efficiency in DEA becomes more interesting when only partial or no information on prices is available. In the extreme case of no price information, assuming non-negative prices, a necessary condition for (3) is that there exists at least one price vector under which y_i and x_j are profit maximizing over the observed sample. As non-negative prices belong to R_+^{m+s}, then

$$\pi^E(\Re_+^{m+s}, x_j, y_i, S) = min_{p_i, w_j \in \Re_+^{m+s}} max_{(x,y)\in S}[p_j(y - y_i) - w_j(x - x_j)/w_j x_j = 1] = 0 \quad (4)$$

where input prices are normalized such that they imply an input cost level of unity for the evaluated vector. Then (4) can be expressed as:

$$\pi^E(\Re_+^{m+s}, x_j, y_i, S) = 1 - max_{p_i\in\Re_+^m, w_f\in\Re_+^s, \theta^*\in\Re}[p_j y_i - \pi^* | w_j x_j = 1, \pi^* \geqslant p_i y - w_j x, (x,y) \in S] = 0 \quad (5)$$

This measure can be interpreted as the actual cost level (equaling unity) minus the required cost level for (x_j, y_i) to be profit maximizing over the sample S. Maximization over prices reveals that most favorable prices are implicitly selected for the evaluated input–output vector, which is considered "benefit-of-the-doubt pricing" in the absence of full price information.

Eq. (6) represents the dual formulation of (5) which measures one minus the maximal equiproportional input contraction (for given output) within the set *CMH*.

$$\pi^{DF}(\Re_+^{m+s}, x_j, y_i, S) = 1 - \min_{\lambda_z\in\Re_+, z=(-x,y)\in S}[\theta | y_i \leqslant \sum_{z\in S}\lambda_z y; \theta x_i \leqslant \sum_{z\in S}\lambda_z x; \sum_{z\in S}\lambda_z = 1] \quad (6)$$

As the second term in (6) gives the *DF* input efficiency measure computed with respect to *CMH*(*S*) in Eq. (2), Cherchye and Van Puyenbroeck (2007) define:

$$\pi^{DF}(z_j, CMH(S)) = min_{\lambda_z\in\Re_+, z=(-x,y)\in S}[\theta | y_i \leqslant \sum_{z\in S}\lambda_z y; \theta x_j \geqslant \sum_{z\in S}\lambda_z x; \sum_{z\in S}\lambda_z = 1] \quad (7)$$

and refer to Eq. (7) as the profit efficiency interpretation of the efficiency measure by Banker et al. (1984) given that $\pi^E(\Re_+^{m+s}, x_j, y_i, S) = 0$ if and only if $\pi^{DF}(z_j, CMH(S)) = 1$.

Profit efficiency as measured by π^{DF} in Eq. (7) using "benefit-of-the-doubt" pricing is represented in Fig. 2. The figure shows the same technology and production points as those in Fig. 1. However, Fig. 2 includes isoprofit lines p_1 and p_2 representing different output-input prices. Looking at point z_3 in the figure, we observe that prices p_1 are the most favorable prices for measuring profits given that any other price ratio measured at the *CMH* (such as p_2) will not improve z_3's profits with respect to those calculated at p_1: $Ox_3(p_2)/Ox_3 < Ox_3(p_1)/Ox_3$. If p_1 represents the most favorable prices for z_3, then it is clear from the figure that z_3 is not as profit efficient as either z_1 or z_2 at those prices and that a linear combination of vectors z_1 and z_2 (on the *CMH*) will result in a more efficient point than z_3. We conclude that z_3 is not profit efficient as there is no price combination that gives us the highest possible profit for the particular combination of outputs and inputs in z_3. Following similar reasoning, it is clear from Fig. 2 that z_1 and z_2 are profit efficient points.

We estimate profit efficiency at the household level for four agroecological zones in Ghana by solving the linear programming problem in Eq. (7) using data from the fifth round of the Ghana Living Standards Survey (GLSS5). Our analysis uses one output (yield) and four inputs: family labor, farm area, value of assets, and purchased inputs (see Appendix for details on the method used to estimate efficiency).

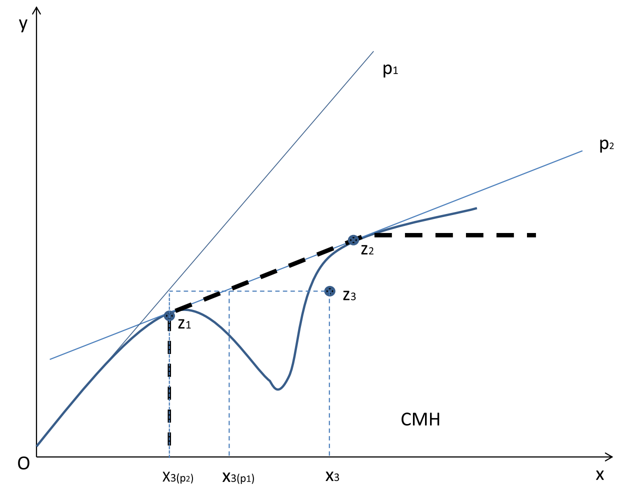

Fig. 2. Profit efficiency measurement with limited information. *Source*: Adapted from Cherchye and Van Puyenbroeck (2007).

Characterization of agricultural production in Ghana

Ghana can be divided into four major agroecological regions in terms of rainfall/climate, vegetation, soil, and growing seasons; these regions provide a diverse environment for agricultural production across the country. From south to north, these agroecological zones are Coastal, Forest, South Savannah, and North Savannah; the general distribution of these AEZs is depicted in Fig. 3. The Forest region receives the most precipitation in the country, between 1500 and 2200 mm/year, while the Coast and the South Savannah regions receive between 800 and 1300 mm/year (FAO, 2013). To the north of the country, precipitation levels are both lower and more erratic; North Savannah receives an average of 1000 mm rainfall per year and is subject to higher average temperatures as well as cold stress risk. Due to the climatic variation across the country, the length of the growing period is greater in the south and shorter in the north (FAO, 2013).

The Coastal region is the most population dense region in the country, but in the 2005 GLSS the region has less than ten percent of total cultivated area. It also has the smallest farm area, smallest share of income from agriculture, and smallest amount of livestock per capita. The Forest region is the major agricultural production region in the country; with about 55% of the total cultivated area, the region supplies more than 90% of the country's total cocoa production. The North Savannah claims one-third of total cultivated land in the GLSS5. This region has the lowest population density (62 people per sq km) and the largest average farm size (4.5 ha per household). It also has a greater percentage of households owning farm equipment than each of the other regions. The north is also the natural livestock region of Ghana due to the lower tsetse fly population there as compared with the humid southern regions of the country. South Savannah is a transition agroecological zone between the Forest and the North Savannah regions; cultivated area in the region it is small relative to other regions, comprising only about 6% of total cultivated area in the country. The Forest region produces about 60% of the country's total value of agricultural production in the 2005 GLSS, with North Savannah and the Coastal region each contributing about 17% and South Savannah less than 10% of total output.

Following the ecological heterogeneity of these zones, agricultural production systems differ throughout the country. Fig. 4 displays the share of the eleven major crops in total household farm area by AEZ. From this disaggregation, we can see several different production systems emerging within each AEZ. Cassava, maize,

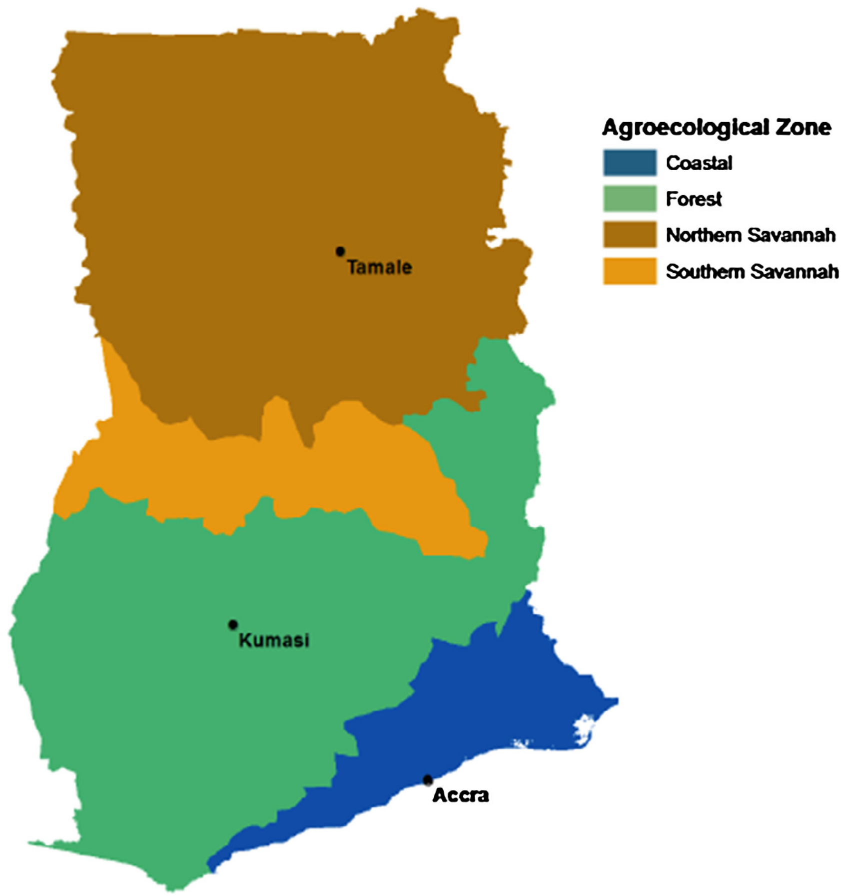

Fig. 3. General distribution of the four agroecological zones of Ghana. *Source*: GLSS5 data elaborated by authors. Note that, due to geospatial data limitations, this figure depicts a stylized representation of the actual distribution of AEZs, depicted at the municipal level.

cocoa, and to a lesser extent yam and plantains, are produced in the Coastal region. The Forest region is dominated by cocoa production but also allocates land to cassava, maize, plantain, yam, and cocoyam. North Savannah is the major millet, rice, sorghum, and groundnut producer in the country and also allocates land to maize, yam, and cassava although less so than do regions to the south. The South Savannah transition zone produces a variety of cereals, including maize, rice, millet, and sorghum, as well as roots, including cassava, yam, and cocoyam and also allocates some land to cocoa production.

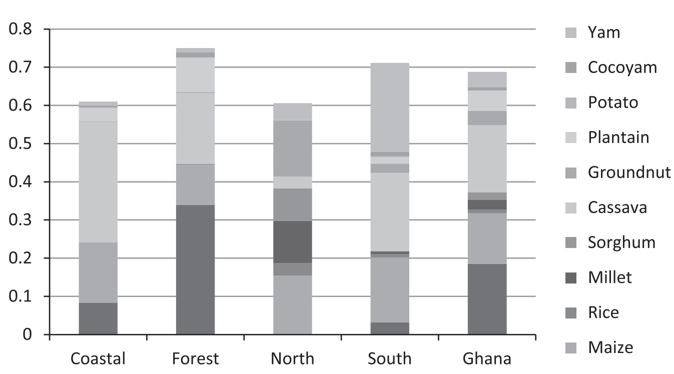

Fig. 4. Reported average share of major crop in total household farm area by agroecological zone. *Note*: The share of crops is calculated as hectares of farm area reported by the household to have this crop as the primary revenue-earning crop in the field over total household farm area. As noted above, total household farm area includes fallow lands owned and all cultivated lands, whether owned or rented. *Source*: GLSS5 data elaborated by authors.

Fig. 5 shows the contribution of each agroecological zone to total output of major crops produced in the country. The Forest region is the main producer of cocoa (95%), cassava (45%) and plantain (80%). The Coastal region is also a major producer of cassava and plantain. Cereals like sorghum/millet and rice are mostly produced in North Savannah. However, the Forest region is the major producer of maize, the main cereal crop in Ghana. Most agricultural supply in Ghana results from production of non-cereal crops. In 2005, the value of all cereals produced in Ghana represented only 20% of the total production value of the three main tropical crops: cocoa, cassava, and plantain. Likewise, total value of cereal production in 2005 represented only 45% of the value of cassava produced that year.

Patterns of agricultural intensification

This section analyzes the intensity in the use of land by looking at the use of purchased inputs and the level of output per hectare in different agroecologies. To do this we group households according to population density, where population density is measured as the number of people per hectare of farm land in the enumeration area where the household is located. We focus on the group of the 30% most efficient households, as determined by the DEA approach explained in the previous section, as we are interested in observing and comparing the most efficient systems at different levels of population density. Note that we do not consider South Savannah in the analysis below due to, as indicated in Section 'Characterization of

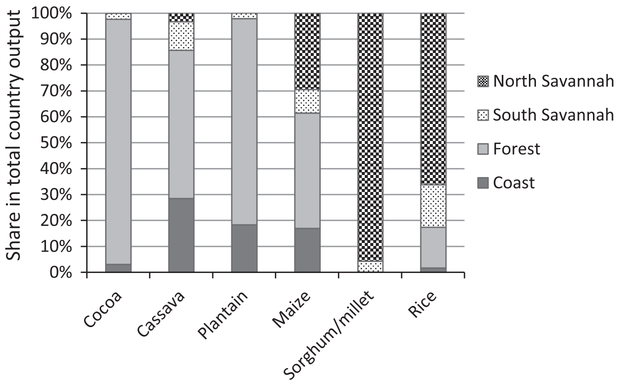

Fig. 5. Contribution of agroecological zones to total output of major crops produced in Ghana. *Source*: GLSS5 data elaborated by authors.

agricultural production in Ghana', the relatively minor role it plays in the agricultural production of the country.

Fig. 6 depicts output and costs per hectare of major inputs extracted from the group of efficient households by population density decile. Notice that economic efficiency is determined using the DEA approach by comparing output, farm land, assets, family labor, and purchased inputs at the household level; here we only show use per hectare of hired labor, fertilizer, and mechanization[5] as major land and labor saving innovations, respectively.

Two distinct patterns emerge from the comparisons in Fig. 6. First, intensification in the Forest region, measured by increases in output per hectare, does not seem to be related to population density until it reaches a threshold of 5 people per hectare of farm land at the highest population density decile. Before that threshold, output per hectare fluctuates around \$1000 and jumps to \$4000 beyond the threshold in high density areas. Second, cash costs per hectare are high at low population densities due mainly to fertilizer use (deciles 2–4); they then decline sharply and increase with population as a result of increases in hired labor and mechanization costs. Fertilizer use does not seem to play any role in the observed increase in output per hectare in high-density regions.

Something similar occurs in the North Savannah where peaks in output and cash costs per hectare occur at low and intermediate levels of population density (deciles 2–3 and 6–7), mostly explained by higher use of fertilizer. Unlike the Forest region, output per hectare falls sharply in high density areas, where there is no fertilizer use and where fewer workers are hired. The Coastal region combines characteristics of the Forest and North Savannah regions, showing fluctuation in output and cash cost per hectare at low and intermediate density levels as in the North Savannah and an increase in output per hectare at high density levels as in the Forest region, but with higher use of fertilizer and mechanization.

What explains these intensification patterns in the different agroecological zones? The key to understanding intensification in the Forest region is comprehension of the central role of cocoa and cassava and the comparative advantage that tree and root crops have over cereals in this production system. According to Vigneri (2007), most of the growth in cocoa production in recent years is the result of increased land area from incorporation of new land in production in relatively low population areas, with contributions of increased labor and fertilizer and the extensive use of spraying machines. Cocoa production in Ghana is characterized by low capital intensity, requiring the use of working capital mainly to hire labor for clearing and weeding the land, and to

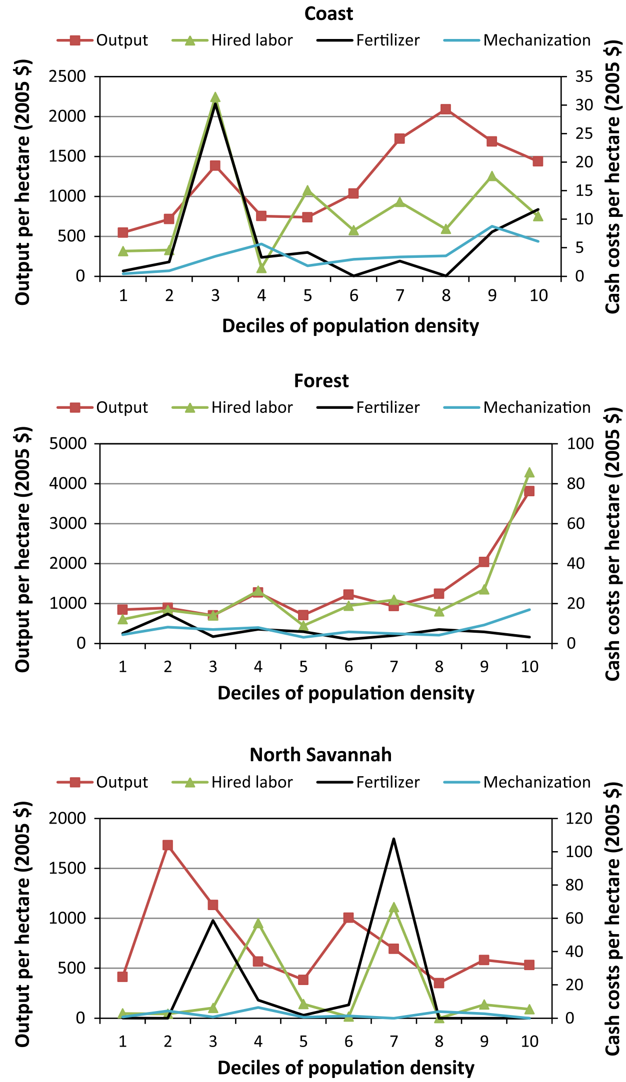

Fig. 6. Output and cash costs of main inputs per hectare of farm land by decile of population density for three agroecological zones in Ghana. *Source*: Elaborated by authors.

purchase chemicals for the control of pests and diseases. Under present circumstances, and in so far as there is still land to be incorporated into cocoa production, there seems to be no incentive to develop a more capital intensive (rather than land intensive) cocoa production. Because of this, in high-density areas with greater land prices and reduced farm size, farmers switch to production of cassava and plantain instead of more intensive cocoa production.

Changes in production and input use with population density for the Forest region are shown in Table 1. The table shows a clear pattern of changes in output composition corresponding with population density, with a falling share of cocoa in total output value (from 19% to 1% of total output value) and an increasing share of cassava in total output (from 38% to 65%). The share of maize in total output is relatively small and varies between 5% and 9% of total output at different levels of population density.

Notice that at the highest population densities there is a significant increase in output per hectare (which triples) with respect to low population density areas and also an increase in cash costs per hectare (which doubles). However, the particular pattern of intensification observed appears to be a strategy to cope with high labor costs and reduced production opportunities in agriculture. First,

[5] In the context of Ghanaian agriculture and the GLSS5 data, mechanization includes tractors, ploughs, carts, spraying machines, and other animal drawn farming equipment.

the increase in output is the result of specialization in cassava production, a crop that can produce high levels of food or returns per worker without high levels of chemical input use. Second, and because of specialization in cassava production, high density areas use less fertilizer per hectare than do low density areas ($5.3/ha and $7.7/ha respectively). Third, the importance of labor costs in high density areas is reflected in higher costs of hired labor and higher use of herbicides per hectare (a labor saving input), both of which are three times larger than in low density areas. Finally, even though the shadow price of land relative to labor is 4.5 times higher in high density areas (Table 1), the opportunity cost of labor employed in agriculture in absolute terms appears to be high, as household income increasingly depends on non-farm activities (non-farm activities compose 57% of total income in high density areas compared with only 26% at low density levels). As households depend less on agriculture, the share of total output that is commercialized decreases from 46% in low density areas to only 20% in high density areas. Results suggest that there are close links between producers in high density areas, the urban sector and non-farm employment opportunities and that it is unrealistic to assume that a surplus of agricultural labor can continue to accumulate among smallholders in a country like Ghana with rising real incomes in the urban sector. Further research is needed to better understand labor markets and labor costs as a constraint to agricultural production.

In summary, producers in high-density areas with high labor cost and small farm sizes face limited opportunities and few incentives to innovate. Most households in these areas follow a strategy that combines income diversification away from agriculture, specialization in cassava to produce high levels of food output without increasing fertilizer use per hectare, and increased used of labor-saving technologies like herbicides and mechanization to reduce the impact of the high opportunity cost of labor.

Table 2 compares output and input composition in areas with different population densities in North Savannah. The first thing to notice is that there is no apparent relationship between population density and intensification. The greatest output per hectare is obtained in areas with low population density while areas with high population density show the lowest output and cash costs per hectare. These results, as in the Forest region, are related to the particular agroecology of the region and to the comparative advantage of crops like yam and rice in different environments.

The greatest production per hectare is obtained in low density areas by a production system specialized in yam production. This crop remains one of the preferred starchy staples in the yam belt of West Africa, and exports of the crop contribute significant foreign exchange earnings to the Ghanaian economy. However, yam is also the most expensive root crop to produce because of the high labor demands for land preparation, planting, staking, weeding, harvesting, and transportation to market (Aidoo et al., 2011). Increased production of yam is constrained mostly by high cost of seed yam, given that 3 to 5 tons per hectare of edible yam of the previous year's harvest may be used to plant a new crop (Aidoo et al., 2011). Continuous production of yam is not possible without large amounts of fertilizer inputs, which gives low population density areas an advantage in producing this crop as land availability allows shifting cultivation and the recovery of soil fertility.

As shown in Table 2, the contribution of yam to total output decreases with population density and the crop is not cultivated in densely populated areas where total farm area is about 1.2 ha compared to more than 5 ha in low density areas. At intermediate levels of population density and smaller farm sizes, yam production falls and is replaced by rice, livestock, and cassava. With high population density, sorghum/millet and livestock increase their contribution to total output.

Table 1
Output and input use in areas with different levels of population density in the Forest region. *Source*: Authors' estimation.

	Population density[c]		
	Low	Middle	High
Population density[a]	0.9	2.1	7.4
Land/labor price	1.0	2.00	4.5
Farm area	4.7	2.08	0.9
Output ($/ha)[b]	759	1028	2362
Cassava	288	440	1541
Plantain	213	303	412
Maize	40	97	141
Cocoa	143	64	24
Other	75	123	244
Yield maize (kg/ha)	1338	798	1230
Yield cocoa (kg/ha)	496	406	396
Yield cassava kg/ha)	17,430	15,478	24,092
Cash cost ($/ha)	40.9	40.3	79.7
Hired labor	14.2	19.0	42.9
Fertilizer	7.7	4.8	5.3
Insecticide	4.5	1.3	1.8
Herbicide	3.7	3.8	7.1
Mechanization	6.5	5.5	10.1
Other	3.4	5.0	11.8
Non-farm income (% of total income)	26	44	57
Share of output sold	46.1	31.6	20.5

[a] Population density is measured as the number of people per hectare of farm land at the enumeration area level.
[b] Output of the different crops is measured as value of output per hectare of farm land: crop values add up to total output per hectare.
[c] The low density group includes the first 3 deciles and the high density group includes the last 3 deciles of the population density distribution.

Table 2
Output and input use in areas with different levels of population density in North Savannah region. *Source*: Authors' estimation.

	Population density[c]		
	Low	Middle	High
Population density[a]	0.84	2.1	5.9
Land/labor price	1.1	1.4	6.1
Farm area	5.5	3.4	1.2
Land/labor	1.08	1.4	6.1
Output ($/ha)[b]	1091	657	489
Sorghum/millet ($/ha)	90	45	255
Maize ($/ha)	92	99	59
Rice ($/ha)	15	92	40
Groundnut ($/ha)	66	125	92
Yam ($/ha)	814	171	0
Livestock ($/ha)	8	35	43
Cassava ($/ha)	7	90	0
Cash cost ($/ha)	30.1	78.3	16.5
Hired labor	3.8	33.3	4.5
Fertilizer	19.6	32.1	0.0
Insecticide	0.0	0.6	0.0
Herbicide	0.0	0.0	0.0
Mechanization	1.9	2.1	2.2
Other	4.7	11.4	9.8
Non-farm income (% of total income)	27	40	53
Share of output sold (%)	42	28	23

[a] Population density is measured as the number of people per hectare of farm land at the enumeration area level.
[b] Output of the different crops is measured as value of output per hectare of farm land: crop values add up to total output per hectare.
[c] The low density group includes the first 3 deciles and the high density group includes the last 3 deciles of the population density distribution.

Cash costs per hectare peak at intermediate population densities associated with rice production ($78 compared to $30 in areas of low population density and only $16 with high density). Most of these costs are due to fertilizer purchases and hired labor. As in the

Table 3
Output and input use in areas with different levels of population density in Coast region. *Source*: Authors' estimation.

	Population density		
	Low	Middle	High
Population density	0.92	2.13	8.81
Land/Labor price	4.42	0.82	3.74
Farm area	3.7	2.1	0.8
Output ($/ha)	599	1055	1736
Cassava	272	655	1149
Plantain	55	198	227
Maize	82	92	199
Cocoa	16	21	6
Tomato	135	15	41
Other	39	74	114
Yield maize (Kgs/ha)	178	499	1084
Yield cassava Kgs/ha)	7560	12,878	13,497
Cash cost ($/ha)	34	26	45
Hired labor	13	9	12
Fertilizer	11	3	7
Insecticide	1	2	1
Herbicide	4	0	4
Mechanization	3	7	12
Other	1	5	10
Non-farm income (% of total income)	21	28	44
Share of output sold	46.1	29.8	37.7

Notes: 1. Population density is measured as the number of people per hectare of farm land at the enumeration area level. 2. Output of the different crops is measured as value of output per hectare of farm land: crop values add up to total output per hectare. 3. The low density group includes the first 3 deciles and the high density group includes the last 3 deciles of the population density distribution.

Forest region, high population density results in income diversification away from agriculture: the share of non-farm income in total income is 53% compared to 27% in low population density areas, while the share of total output that is sold in the market is only 23% compared to 42% in low density areas.

Table 3 shows that cassava is the most important crop in the Coastal region and higher production per hectare in high population density areas results from higher production per hectare of cassava, which increases its share in total output per hectare from about 45% ($277 in a total of $599 per hectare) to more than 60% ($1149 in a total of $1736). Output of plantain and maize also increases in high density areas, while tomato production shows a significant contribution to total output in low density areas. The importance of tomato in low density areas could be related to intensive use of fertilizer and hired labor in these areas, similar to those in high density areas. Overall, the level of input per hectare in the Coastal region appears to be low compared to that in other regions, despite favorable conditions for market access, infrastructure and population density.

In conclusion, we observe that the use of chemical inputs and the greatest output per hectare do not appear to be driven by increasing population density, as these phenomena occur within a wide range of population densities and are associated with specific crops like cocoa in the Forest region, yam and rice in the Savannah, and tomato in the Coast. We observe also that in high population density areas, households depend more on non-farm income; they use fewer chemical inputs and reduce their participation in output markets. While the above discussion is based on patterns observed among the most efficient households, note that these results generally hold over the entire sample.

Land- or labor-saving technologies?

To shed light on the profitability of chemical inputs and labor-saving technologies like mechanization, we group households into three groups—low, middle, and high efficiency—based on our measure of economic efficiency; we then compare input use and production of different agricultural activities between the low and high efficiency groups. Table 4 presents this comparison showing output value of different activities and cash cost categories per hectare of farmland.

Comparisons of efficient and inefficient producers within the Forest region (captured in the first three columns in Table 4) show that efficient producers attain 150% more output than inefficient producers and that more than 90% of this difference is explained by higher production of cassava and plantain ($91 more per hectare of cassava and $44 more of plantain). This higher output is produced by spending almost half of the total cash costs incurred by the inefficient group. This difference in costs is mostly the result

Table 4
Differences in output composition and input use between efficient and inefficient producers. *Source*: Authors' estimation.

	Forest			North Savannah			Coast		
	Inefficient	Efficient	Difference	Inefficient	Efficient	Difference	Inefficient	Efficient	Difference
Output	493	1227	149	185	722	291	491	1307	166
Maize	73	86	3	46	79	18	92	141	10
Cocoa	81	85	1	–	–	–	2	14	2
Cassava	189	632	90	1	68	36	246	808	114
Plantain	93	309	44	–	–	–	29	205	36
Yam	23	76	11	34	355	174	62	50	−3
Rice	1	3	0	13	29	9	0	1	0
Millet	–	–	–	20	39	10	–	–	–
Sorghum	–	–	–	16	32	9	–	–	–
Groundnut	–	–	–	31	93	34	0	1	–
Tomato	6	26	4	2	6	2	6	44	8
Livestock	27	10	−3	22	21	−1	53	43	−2
Cash cost	92	50	−46	33	30	−9	123	32	−74
Hired labor	28	22	−7	11	10	−3	41	11	−24
Chemicals	39	13	−28	12	14	6	48	8	−33
Fertilizer	23	6	−18	11	14	9	24	5	−15
Insecticide	8	3	−5	1	0	−3	8	1	−5
Herbicide	9	5	−4	0	0	0	17	2	−12
Mechanization	7	7	0	4	1	−9	7	4	−2
Livestock costs	5	1	−4	3	2	−3	19	1	−14
Other costs	11	5	−7	4	2	−6	7	6	−1

Notes: 1. Represents the differences in output value and input costs between efficient and inefficient producers. Figures for each crop or cost item add up to the percentage difference of output value or total input cash cost, respectively.

Table 5
Regression results of the model underlying the Analysis of Variance of the rank of profit efficiency[a] on intensity of input use (low or high) and share of different crops in total output (low, intermediate, or high), Forest region. *Source*: Authors' estimation.

Independent variable: Output share or input intensity[b]	Coefficient	Std. Err.	*t*	*P* > *t*
Cocoa (High)	37.956	63.7	0.60	0.551
Cassava				
(Intermediate)	−110.5	82.9	−1.33	0.183
(High)	−39.2	59.4	−0.66	0.509
Maize				
(Intermediate)	−23.3	58.2	−0.40	0.689
(High)	−229.2	64.9	−3.53	0.000
Other tree crops				
(Intermediate)	3.4	76.6	0.04	0.965
(High)	−46.5	58.5	−0.79	0.427
Fertilizer/ha (High)	−374.2	116.2	−3.22	0.001
Herbicide/ha (High)	−251.5	107.6	−2.34	0.019
Mechanization/ha (High)	−635.0	79.2	−8.02	0.000
Insecticide/ha (High)	−179.7	112.7	−1.59	0.111
Farm area (High)	−599.5	86.4	−6.94	0.000
Mech * Fert				
(High) * (High)	225.7	63.9	3.53	0.000
Herb * Mech				
(High) * (High)	136.0	58.9	2.31	0.021
Mech * Insect				
(High) * (High)	186.5	63.7	2.93	0.003
Cassava * Mech.				
(Intermediate) * (High)	248.9	80.7	3.08	0.002
(High) * (High)	184.0	66.3	2.77	0.006
TreeCrops * Mech				
(Intermediate) * (High)	153.6	79.1	1.94	0.052
(High) * (High)	135.9	66.0	2.06	0.040
Cassava * Insect.				
(High) * (High)	−146.3	84.0	−1.74	0.082
Cocoa * Insect.				
(High) * (High)	−133.6	74.0	−1.80	0.071
FarmArea * Cocoa				
(High) * (High)	145.3	62.9	2.31	0.021
FarmArea * TreeCrops				
(Intermediate) * (High)	146.3	80.5	1.82	0.069
(High) * (High)	187.7	67.5	2.78	0.005
FarmArea * Mech.				
(High) * (High)	139.1	57.9	2.40	0.016
FarmArea * Insect.				
(High) * (High)	132.3	68.5	1.93	0.054
Constant	1687.626	67.95198	24.84	0.000

Number of obs. = 2112
$F(59, 2052) = 12.630$
Prob > F = 0.000
R-squared = 0.249
Adj R-squared = 0.229
Root MSE = 544.090

[a] The dependent variable is a rank of profit efficiency taking values between 1 and 2176 for the lowest and highest values, respectively, of efficiency, as estimated by DEA.
[b] Crop variables are categorical variables defined as "low", "intermediate" or "high" based on the share of that crop in total output. Inputs are categorical variables defined as "low" or "high" based on the intensity of input use per hectare. All comparisons are with respect to the group of producers using low levels of each variable. For example, producers with high shares of maize in total output show significantly lower efficiency rankings (229.2 points lower) than the average ranking of producers with low maize shares in total output. No differences in efficiency are observed between low and intermediate maize shares in total output.

of the efficient group spending less on fertilizer; however, this doesn't mean that the efficient farmers are so because they use a little less fertilizer than the inefficient farmers. The vast majority of these efficiency differences pertain to crop choice; very few can be accounted for by input differences. In particular, efficient producers produce more cassava and plantain, which generates an output that is four times greater than that of inefficient producers at a cost that is half that of the inefficient producers.

Comparisons for the North Savannah region (captured in columns four to six of Table 4) show that production of yam, and to a lesser extent of cassava and groundnuts, creates the difference between the efficient and the inefficient group. Differences in input costs per hectare are small and appear to be less important than outputs in explaining efficiency differences. Input use per hectare is similar in both groups but efficient producers use more fertilizer than inefficient producers.

Efficiency in the Coastal region appears to be related to cassava production, the main crop in the region. Efficient farmers produce 166% more per hectare than inefficient producers and almost 70% of this difference is explained by higher production of cassava. The rest is due to greater production of plantain and tomato. At the same time, efficient farmers produce with lower hired labor and chemical input costs.

While Table 4 offers a first look at the different practices of efficient and inefficient producers, Tables 5–7 present a more rigorous analysis of these differences. In the ANOVA analysis presented in these tables by region, we use ranks of economic efficiency values, as determined by DEA, as the dependent variable.

Results of the ANOVA analysis for the Forest region show significant negative correlations between chemical inputs, mechanization, and farm size and efficiency, meaning that farms using high input levels and farms with large areas tend to be inefficient. More

Table 6
Regression results of the model underlying the Analysis of Variance of the rank of profit efficiency[a] on intensity of input use (low or high) and share of different crops in total output (low, intermediate, or high), North Savannah region. *Source*: Authors' estimation.

Independent variable: output share or input intensity[b]	Coefficient	Std. Err.	t	$P > t$
Rice (High)	108.0	44.8	2.41	0.016
Sorghum/millet (High)	238.1	57.4	4.15	0.000
Maize				
(Intermediate)	129.1	57.4	2.25	0.025
(High)	141.0	53.3	2.65	0.008
Groundnuts (High)	155.9	45.2	3.45	0.001
Yam (High)	163.0	85.7	1.90	0.057
Cassava				
(Intermediate)	−116.5	318.8	−0.37	0.715
(High)	72.6	203.8	0.36	0.722
Fertilizer/ha (High)	23.0	95.6	0.24	0.810
Herbicides/ha (High)	−135.5	278.7	−0.49	0.627
Mechanization/ha (High)	−4.3	84.0	−0.05	0.959
Insecticide/ha (High)	307.6	185.4	1.66	0.097
Farm area (High)	55.1	86.8	0.63	0.526
Mech * Fert.				
(High) * (High)	106.2	54.1	1.96	0.050
Maize * Fert				
(High) * (High)	−136.1	70.4	−1.93	0.054
SorghMill/Fert				
(High) * (High)	−155.8	66.3	−2.35	0.019
Rice * Mech				
(High) * (High)	−136.1	50.1	−2.72	0.007
Yam * Insect				
(High) * (High)	−330.6	121.6	−2.72	0.007
Constant	465.8	65.2	7.15	0.000

Number of obs. = 1558
$F(59, 2052) = 4.960$
Prob > F = 0.000
R-squared = 0.166
Adj R-squared = 0.132
Root MSE = 430.470

[a] The dependent variable is a rank of profit efficiency taking values between 1 and 1605 for the lowest and highest values, respectively, of efficiency, as estimated by DEA.
[b] Crop variables are categorical variables defined as "low", "intermediate" or "high" based on the share of that crop in total output. Inputs are categorical variables defined as "low" or "high" based on the intensity of input use per hectare. All comparisons are with respect to the group of producers using low levels of each variable. For example, producers with high shares of maize in total output show significantly higher efficiency rankings (141 points higher) than producers with low maize shares in total output.

relevant for our analyses, however, are the interaction terms in Table 5 (note that we only report those showing statistically significant coefficients). Results show that the use of chemical inputs increases efficiency if combined with mechanization. They also show that farms with large areas become efficient when they use mechanization or when they specialize in the production of cocoa or other tree and root crops.

ANOVA results for the North Savannah (Table 6) show that we cannot associate any particular crop with inefficiency. On the other hand, the non-significance of the coefficients on inputs per hectare, and the negative coefficients obtained when greater use of purchased inputs is combined with greater shares of maize, sorghum/millet, and yam in total output, suggest that high fertilizer use is not correlated with efficiency. As in the Forest region, the use of fertilizer together with mechanization results in improves efficiency.[6]

Finally, Table 7 shows that intermediate and high shares of cassava and high shares of maize in total output are correlated with higher efficiency in the Coastal region while mechanization and the use of herbicides are negatively correlated with efficiency. The interaction terms, on the other hand, reveal that the labor-saving combination of herbicides and mechanization is correlated with higher economic efficiency. We do not find evidence of a positive effect of fertilizer on efficiency in the Coastal region.

In summary, our results show that economic efficiency in the Forest region is negatively correlated with high levels of chemical inputs, fertilizer in particular, and high shares of maize in total output. On the other hand, the use of inputs combined with mechanization and larger farm size is correlated with higher efficiency in the Forest and the Savannah regions while mechanization and herbicides, when used together, are correlated with higher efficiency in the Coastal region. These findings confirm that some of the most productive regions in Ghana have a comparative disadvantage in cereals as well as a lack of incentive to intensify cereal production when most production occurs in low-density areas with relatively abundant land and scarce labor in competition with root and tree crops. In the case of the North Savannah region, the use of chemical inputs results in improved efficiency only when combined with mechanization.

Conclusions

With African agricultural development again a priority on many policy and research agendas, there has been renewed interest in the lessons of the Asian Green Revolution as well as renewed government support for input promotion programs and subsidies. As in the past, the focus of these policies and programs remains on land-saving, labor-intensive technologies that entail intensive use

[6] In the case of the North Savannah, where many areas outside of river flood plains and creek beds are not suitable for rice production, the assumption of a unique production possibility space could be invalid as the results of efficiency estimates could be biased toward households in most favorable environments. However, we do not think this is a constraint for our analysis as we are only interested in getting an idea of which are the most efficient systems and practices at different input combinations. From this point of view, the difference of the rice agroecology could be a problem if rice producers dominate all others in terms of efficiency and we only get rice production as the efficient option in the Savannah. Results of the ANOVA show that this is not the case.

Table 7
Regression results of the model underlying the Analysis of Variance of the rank of profit efficiency[a] on intensity of input use (low or high) and share of different crops in total output (low, intermediate, or high), Coastal region. *Source*: Authors' estimation.

Independent variable: output share or input intensity[b]	Coefficient	Std. Err.	*t*	*P* > *t*
Cocoa (High)	44.3	61.2	0.72	0.469
Cassava				
(Intermediate)	213.4	92.2	2.31	0.021
(High)	98.6	40.6	2.43	0.015
Maize				
(Intermediate)	−48.6	52.5	−0.93	0.355
(High)	102.4	40.0	2.56	0.011
Other tree crops				
(Intermediate)	6.7	43.5	0.15	0.878
(High)	−9.5	32.8	−0.29	0.772
Fertilizer/ha (High)	−25.0	87.5	−0.29	0.776
Herbicides/ha (High)	−208.8	86.0	−2.43	0.015
Mechanization/ha (High)	−110.6	43.5	−2.54	0.011
Insecticide/ha (High)	−99.0	98.1	−1.01	0.313
Farm area (High)	−102.9	44.7	−2.31	0.021
Herb. * Mech.				
(High) * (High)	137.4	50.8	2.70	0.007
Maize * Mech.				
(Intermediate) * (High)	79.4	39.9	1.99	0.047
(High) * (High)	−89.4	42.2	−2.12	0.034
Cassava * Insecticide				
(Intermediate) * (High)	150.7	79.1	1.91	0.057
(High) * (High)	131.4	66.0	1.99	0.047
Other tree crops * Insecticide				
(Intermediate) * (High)	143.9	80.4	1.790	0.074
(High) * (High)	186.3	67.5	2.760	0.006
Constant	400.6	37.9	10.57	0.000

Number of obs. = 655
$F(59, 595) = 5.41$
Prob > F = 0.0000
R-squared = 0.3491
Adj R-squared = 0.2846
Root MSE = 175.87

[a] The dependent variable is a rank of profit efficiency taking values between 1 and 735 for the lowest and highest values, respectively, of efficiency, as estimated by DEA.
[b] Crop variables are categorical variables defined as "low", "intermediate" or "high" based on the share of that crop in total output. Inputs are categorical variables defined as "low" or "high" based on the intensity of input use per hectare. All comparisons are with respect to the group of producers using low levels of each variable. For example, producers with high shares of maize in total output show significantly higher efficiency rankings (102 points higher) than producers with low maize shares in total output. No differences in efficiency are observed between low and intermediate maize shares in total output.

of fertilizers and high yielding varieties. This renewed optimism about the possibility of an Asian-style Green Revolution taking root in Africa overlooks, once again, some of the structural characteristics of African agriculture; this oversight is likely due to the assumption that rapid population growth on the continent will bring Africa closer to the situation of many Asian countries at the beginning of the Green Revolution.

We claim that such an assumption could again result in a frustrated attempt to promote agricultural growth in Africa. Adding to the fact that vast areas of agricultural land in African countries are still under low population pressure, most countries in the region are natural resource rich economies that are structurally different from labor-abundant economies and that will not necessarily be transformed in low labor cost economies by population growth. High labor costs can arise and persist in settings of high rural population density combined with specialization in natural resources; such settings are found not only in Ghana, but also in many African countries. For example, half of all Sub-Saharan African countries are classified by Treviño and Thomas (2013) as "resource intensive," countries where oil and mineral exports exceed 25% of total merchandise exports. And this list of resource intensive SSA countries could be extended if one were to include those countries with comparative advantage for agricultural production and significant resource export potential. The persistence of high labor costs in these countries suggests that the process of intensification and structural change in Africa could be very different from that observed in Asia.

In this study we look at the case of Ghana to identify whether fast population growth and the remarkable agricultural performance the country has enjoyed in recent years have resulted in favorable conditions for the adoption of Asian-style Green Revolution land-saving technologies by responding to two main questions: Is fertilizer use in Ghana correlated with high population density regions and intensive cereal production? Are land-intensive, rather than labor-intensive, innovations correlated with more efficient production practices?

Although, given the limitations of our data and approach, definitive conclusions cannot be reached, we find no evidence of agricultural intensification in Ghana following an Asian-style Green Revolution. Specifically, we find no correlation between population density and input intensity. Nor do we find correlation between input use and cereal production. Moreover, we do find evidence that labor costs still play a major role in limiting the adoption of labor-intensive technologies even in high population density areas in all major agroecologies in Ghana.

We summarize these findings as follows. First, the use of chemical inputs mostly occurs in low population density areas where commercial opportunities are correlated with the suitability of natural resources to produce cocoa, cassava, yam, and rice. Second, consistent with Goldman (1993), we find that in very population dense areas of the Forest, North Savannah, and Coastal regions, and in response to a combination of high labor costs and small farm areas, producers reduce their participation in output and input markets, diversify income away from agricultural activities, and specialize in crops like cassava that can produce large quantities of food and high returns per worker. Third, with most commercial production occurring in low density, relatively land-abundant areas facing labor constraints, the impact of land-saving innovations like fertilizer on economic efficiency is low or negative, with most efficient producers using fewer chemical inputs than inefficient ones. Notably, however, when combined with a labor-saving innovation like mechanization, we find that the use of fertilizer is related to greater economic efficiency.

Finally, these findings have implications for technology adoption in Ghana. First, the possibility of an Asian-style Green Revolution surging in high population density areas of Ghana is a very unlikely outcome, as conditions in Ghana are much like those observed by Goldman and Smith (1995) in West Africa: the agricultural sector is characterized by very small farms, low farmer incomes, minimal use of modern purchased inputs, low market participation, diversification to non-farm activities and high labor costs. Second, if intensification is market-driven and based on profitable crop production, most opportunities will be found in areas where land is relatively abundant or at least does not constrain investment and expansion of production and where producers can combine a more intensive use of chemical inputs with labor saving innovations and investments that increase labor productivity.

The DEA efficiency model

The profit efficiency interpretation of Banker et al.'s (1984) efficiency measure as defined in Eq. (7) is estimated for each household in our sample by solving a linear programming problem. For a particular household $s = 1$ included in $s = \{1,\ldots,S\}$, producing one output (y) and four inputs x_j, $j = \{1,\ldots,4\}$, efficiency is estimated as:

$$\underbrace{\textit{Minimize}:\ \theta_1}_{\lambda\ \theta_1}$$

$$\text{subject to} \quad \sum_{s=1}^{S} y_s\lambda_s \geq y_1 \qquad \sum_{s=1}^{S} x_{sj}\lambda_s \leqslant x_{1j}\theta_1 \ \text{with}\ j = 1,\ldots,4 \qquad \sum_{s=1}^{S}\lambda_s = 1 \tag{A.1}$$

This problem tests for profit maximization using the most favorable prices, which are implicit shadow prices in this dual formulation of the profit maximization problem in Eq. (5). Because "most favorable prices" do not exclude zero prices, a correction is needed when the solution to the linear programming problem includes zero prices for one or more of the inputs. This is because we label a netput vector as profit efficient if and only if it is profit maximizing under strictly positive prices. With zero prices, the efficiency parameter θ could be labeling a netput vector as efficient even though we might still be able to further reduce some individual inputs to produce the same amount of output. This possibility can be seen in Fig. 2 considering a production unit z_0 (not shown in the figure) using the same level of input as z_1 but located on the dotted vertical line below z_1. Reference shadow prices for z_0 are represented by the vertical line passing through z_1 (output price =0). If there are no production units to the left of the vertical line, z_0 will be at the "frontier" of the production space even though it is clearly inefficient because it produces less output than z_1 using the same amount of input. In other words, z_0 is labeled as profit efficient like z_1 only because it is evaluated at zero output price. With strictly positive prices, z_0 is profit inefficient. Cherchye and Van Puyenbroeck (2007) solve this problem by searching for an alternative reference vector for z_0 with strictly positive prices. Intuitively, they used z_1 as the reference for z_0 in Fig. 2 and measure the distance between both points using a normalized metric to define a mixed efficiency measure:

$$\theta^M = \sqrt{(y_0/y_1)^2 + (x_0/x_1)^2}$$

This distance measure will reveal z_0 as inefficient because $x_0 = x_1$ and $y_1 > y_0$ resulting in $\theta^M < 1$. By comparing all efficient points to other frontier points using this metric we can identify points labeled as efficient with (A.1) when the solution to this problem includes at least one zero shadow price. In the multidimensional case Cherchye and Van Puyenbroeck (2007) show that this metric is equivalent to solve the following linear programming problem:

Mixed efficiency for household 1:

$$\underbrace{\textit{Minimize}}_{\lambda\ \theta^M_{j1}} \quad \sqrt{\frac{\sum_{j-1}^{4} - \theta_{1j^M}}{4}}$$

$$\text{subject to} \quad \sum_{s} = 1^S y_s\lambda_s \geqslant y_1 \qquad \sum_{s=1}^{S} x_{sj}\lambda_s \leqslant (\theta_1 x_{1j})\theta^M_{i,j} \ \text{with}\ j = 1,\ldots,4 \qquad \sum_{s=1}^{S}\lambda_s = 1 \tag{A.2}$$

where the parameter θ_1 in the input constraint is the solution to (A.1), meaning that we use efficient levels of inputs for household 1. Notice that (A.2) minimizes the arithmetic mean of the unidimensional input contraction factors instead of finding one value that reduces all inputs in the same proportion as in (A.1). The final measure of profit efficiency used for the analysis combines estimated efficiency in (A.1) and (A.2):

$$\theta^\pi = \theta \times \theta^M$$

In this study we estimate the three efficiency measures for all households in our sample and consider profit efficient households those that are efficient under strictly positive prices. This is the case if $\theta^\pi = \theta = \theta^M = 1$.

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