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Paving the Way for Development?

The Impact of Transport Infrastructure on Agricultural Production and Poverty Reduction in the Democratic Republic of Congo

John Ulimwengu

Jose Funes

Derek Headey

Liangzhi You

Knowledge, Capacity, and Innovation Division

Development Strategy and Governance Division

Environment and Production Technology Division

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AUTHORS

John Ulimwengu, International Food Policy Research Institute
Postdoctoral Fellow, Knowledge, Capacity, and Innovation Division

Jose Funes, International Food Policy Research Institute
Senior Research Assistant, Development Strategy and Governance Division

Derek Headey, International Food Policy Research Institute
Research Fellow, Development Strategy and Governance Division

Liangzhi You, International Food Policy Research Institute
Senior Scientist, Environment and Production Technology Division

Notices

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[2] IFPRI Discussion Papers contain preliminary material and research results, and have been peer reviewed by at least two reviewers—internal and/or external. They are circulated in order to stimulate discussion and critical comment.

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ABSTRACT

Given its vast land resources and favorable water supply, the Democratic Republic of Congo's (DRC's) natural agricultural potential is immense. However, the economic potential of the sector is handicapped by one of the most dilapidated transport systems in the developing world (World Bank 2006). Road investments are therefore a high priority in the government's investment plans and those of its major donors. Although these are encouraging signs, very little is known about how the existing road network constrains agricultural and rural development, and how proposed new road investments would address these constraints. To inform this issue, the present paper primarily employs geographic information system (GIS)-based data to assess the impact of market access on agricultural and rural development in the DRC. Compared to existing work, however, the paper employs a number of innovations to improve and extend the generic techniques used to estimate the importance of market access for agricultural and rural development. We then use our derived results to run simulations of how proposed infrastructure investments would affect market access, and how market access would in turn affect agricultural production and household wealth. We find highly significant and negative elasticities between travel times to sizable cities (50,000 or 100,000 population), although we also find that these elasticities are small relative to those of similar cross-country tests. Moreover, city access by itself is less important than access to cities and ports. This finding strongly suggests that increasing investment in ports in the DRC should be a priority in the infrastructure investment portfolio.

Keywords: Democratic Republic of Congo, infrastructure, market access, road and river transport, agricultural production, poverty

1. INTRODUCTION

The agricultural potential in the Democratic Republic of Congo (DRC) is immense. By one back-of-the-envelope calculation, if yields in the DRC's 80 million hectares of arable land were to catch up to the global technological frontier, the country could feed around one-third of the world's population.[1] But sheer biophysical potential is not the same as economic potential. Decades of conflict, corruption, and economic mismanagement have severely weakened the socioeconomic base of the country. Between 1960 and 2001, the DRC experienced the largest economic decline in the world (less than -3 percent GDP growth per year), and the vast agricultural sector—which employs over three-quarters of the population—has suffered particularly badly. Agricultural exports declined from 40 percent of all exports in 1960 to only 10 percent in 2000, and the food surplus per person declined by an astonishing 30 percent between 1975 and 2000. Around two-thirds of the country lives on less than US$1 per day, at least 70 percent face food insecurity of some sort while 16 million people suffer from chronic malnutrition, crop yields are a minuscule fraction of their potential, and the country imports around one-quarter of its cereal consumption. Yet, paradoxically, agriculture's share in gross domestic product (GDP) has actually increased because of the declining mining and manufacturing, so the usual path of structural transformation has been reversed. In short, the DRC is a severely depressed economy in which the vast majority of the population survives in a subsistence agricultural economy (see key indicators in Table 1).

Table 1. Key indicators of the state of agriculture and welfare in the DRC

	DRC	Africa	LATAC	East Asia	South Asia	MENA
Global Hunger Index[a] (1–100)	25.1	24.4	8.9	14.0	24.8	7.8
Net agricultural exports[b] (% total imports)	-4.2	15.3	13.0	10.2	-2.0	-4.7
Net food exports[b] (% imports)	-7.3	-2.7	5.6	1.0	-1.7	-2.8
Cereal imports[c] (% cereal consumption)	27.0	37.5	44.2	16.4	10.0	49.4
GDP per capita[d] (2000 international dollars)	272	2,309	7,432	4,548	2,079	5,547
Rural population[d] (% total)	67.3	62.0	35.2	61.4	75.8	40.5

Source: a. von Grebmer et al. (2008); b. Aksoy and Dik-melik (2008); c. FAO (2008); d. World Bank (2006)
Notes: Only low- and middle-income countries are included. LATAC is Latin America and the Caribbean, and MENA is the Middle East and North Africa. "Africa" refers only to Sub-Saharan Africa.

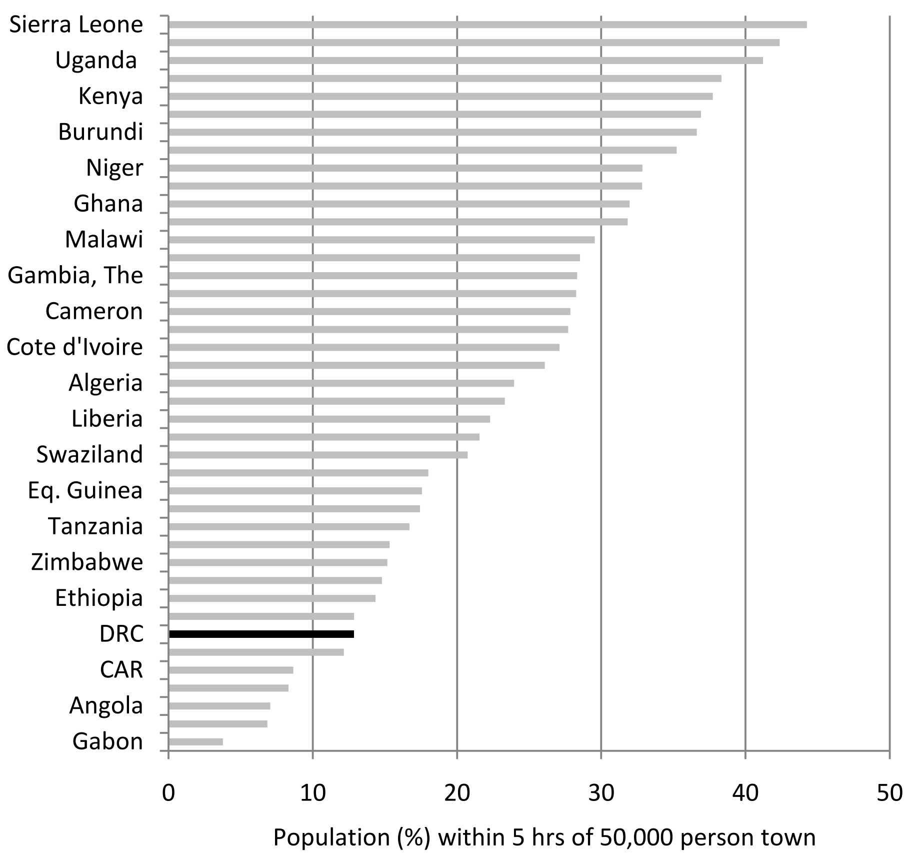
Despite being the third-largest country in Africa and one of the poorest, the question of how to reverse decades of economic stagnation in the DRC is one that the research community has scarcely touched upon. Although we know that agriculture is important even in mineral-rich economies (e.g., Indonesia, Chile, and Nigeria), achieving agricultural growth requires not only a range of investments *in* agriculture (research and development, extension services, irrigation projects, input distribution policies, etc.) but also investments *for* agriculture. In the case of the DRC, we argue that it is actually an investment for agriculture—rural roads—that is currently the binding constraint on agricultural growth. Our reasoning is quite simple. First, a range of studies have demonstrated that roads are extremely important for agricultural development (see Van de Walle 2002), and that weak transport infrastructure is an especially severe constraint across much of Africa. Second, transport infrastructure in the DRC is

[1] Eric Tollens, professor and agronomist at the Catholic University of Leuven, Belgium, quoted by La Voix du Congo Profond, the magazine of the Belgian Development Cooperation, Issue No. 4, pp. 32–33.

particularly weak (Minten and Kyle 1999; World Bank 2006). Figure 1 shows the percentage of the population estimated to be within five hours' drive of a 50,000-person town. The DRC has one of the lowest "market access" scores in Africa, and we will suggest below that these estimates almost certainly overestimate market access on the ground. For one thing, many roads in the DRC are roads in name only, and survey evidence suggests that transport times are also increased by around 40 percent in the wet season, which in the DRC lasts for almost half the year.

Finally, as our title suggests, rural roads are somewhat unique in terms of their capacity to literally pave the way for other investments, such as schools, health services, and security services (AITD and UNESCAP 2000; Fan 2008). In agriculture, better roads can drastically reduce the cost of inputs such as fertilizers, seeds, and extension services (Ali and Pernia 2003; Gregory and Bumb 2006; Ahmed and Hossain 1990; Cicera and Arndt 2008; Dercon et al. 2008). On the output side, better roads increase the scope of profitable trade, which in turn encourages on-farm investments to raise agricultural production (Binswanger, Khandker, and Rosenzweig 1993; Khachatryan et al. 2005). This in turn should raise rural incomes, lower food prices (and hence raise disposable incomes in urban areas), reduce spatial disparity in food prices, and reduce dependence on food imports. Hence, better rural roads increase net returns to other worthy investments in both the farm and nonfarm sectors.

Figure 1. GIS-based estimates of market access in Sub-Saharan Africa



Source: Authors' calculations.
Note: DRC=Democratic Republic of Congo. CAR=Central African Republic..

It is also reassuring to note that we are by no means alone in identifying infrastructure as a severe bottleneck in the DRC's development, particularly with regard to agricultural growth. A recent World Bank review attributes the decapitalization of the DRC's agricultural sector to the collapse of the country's infrastructure network and identifies infrastructure investments as one of the four critical policy goals for the sector. The DRC government and its donors have likewise identified infrastructure as a priority sector. The World Bank and British government have signed a five-year agreement for the rehabilitation and upgrading of 1,800 kilometers of high-priority roads. These projects have already made it possible to open 4,200 kilometers of roads and will thus make it possible to cover more than 40 percent of the 15,000 kilometers of roads that have been identified as priority investments in the DRC. Finally, China is now becoming a major international investor in the DRC. The financial crisis and political tensions with traditional donors there have led to substantial delays in the negotiations between the DRC and China, but as of mid-2009 China's road investments are once again going ahead. If indeed they do proceed, the partnership would constitute one of the largest infrastructure investments in African history, including around 5,800 kilometers of road rehabilitations and an equally long railway network.

Although these infrastructure investments in principle address a binding constraint on the DRC's economy, they also involve risks. First, debt-funded investments need to generate high returns in order to offset the debt burden. Second, infrastructure may be a generic solution to the DRC's problem, but the spatial allocation of infrastructure investments might significantly determine their broader socioeconomic impact. Africa as a whole has a checkered history in which infrastructure investments—including colonial investments—often served extractive industries rather than agriculture. Given the DRC's vast mineral wealth, the possibility that roads could serve the mineral sector well but again bypass agriculture is very real. Hence, in addition to gauging the relationship between roads and agricultural development in the DRC, we also go one step further in using those results to simulate the impacts of the recent infrastructure proposals on agricultural production.

The methods by which we do so build on existing techniques, although we extend and adapt these techniques in several ways (Section 2). First, we follow the burgeoning "GIS literature" in estimating market access based on imposing simple travel-time assumptions on geo-referenced maps of the DRC road network, as we did for the statistics in Figure 1. However, because these assumptions are derived from generic travel-time assumptions rather DRC-specific assumptions, we adapt the estimates to the DRC's circumstances using survey-based travel-time estimates from Minten and Kyle (1999). We then re-estimate the likely impact of the DRC's planned infrastructure investments on market access across the country, as well as other scenarios such as a "transport network" investment strategy and a comprehensive "rural feeder road" strategy. Section 2 also outlines our methodologies for estimating crop production potential, actual crop production, and population density.

In Section 3 we look at the relationship between infrastructure and poverty using the 2007 Demographic Health Survey (DHS) for the DRC. This allows us to get a sense of how infrastructure–poverty linkages vary over different regions in the DRC, as well as over the agricultural and nonagricultural populations. In Section 4 we look at the more specific relationship between agricultural production and market access using the methodology described in Section 2. To begin with, we econometrically estimate the impact of market access on crop production, following Dorosh et al. (2009). Finally, in Section 5, these various elasticities between market access and welfare outcomes are used to simulate the impacts of alternative road investment strategies, including the current proposals of the DRC government and its development partners. Section 6 provides a concluding discussion.

2. METHODS

In this section we outline the methods use to construct a geospatial dataset that includes crop production, a measure of market access that effectively links population distribution with transport infrastructure and terrain characteristics, and a measure of agroclimatic crop suitability that accounts for the biophysical potential of physical areas in terms of soil and climatic suitability. We then discuss our econometric strategy for establishing the relationships between these variables.

2.1. Population Data in the DRC and Local Market Access

In the DRC there were previously 11 provinces, although these were broken up into 26 provinces in 2006. However, many of the statistics and discussions in subsequent sections utilize the original 11 provinces, so Figure 2 provides a reference to the locations of these provinces and the major cities listed in Table 2. Figure 2 shows the locations of these cities and the "old" provincial boundaries (bolder lines) as well as the new provinces (gray lines) and territories (faint gray lines).

The total population of the DRC is not known very precisely, but in 2009 the United Nations estimated the population at 66 million, having increased rapidly, despite the war, from 46.7 million in 1997. The urban population is estimated to be around 30 percent, and the DRC is estimated to have the third youngest population in the world, with a median age of just 16.5. The largest cities in the DRC are listed in Table 2. With three cities of over 1 million inhabitants, urban markets in the DRC are certainly large, although urban agriculture is also not unknown. Kinshasa, with over 7 million people, is undoubtedly a large market and is a major destination for agriculture produce from neighboring provinces such as Bandundu. As for the old provinces, most have 3–6 million people, with Bandundu, Orientale, Equateur, and Katanga being the most populous. However, more recent data on the 26 new provinces suggest that Kinshasa and North and South Kivu are now the most populous provinces.

Table 2. City sizes in the DRC, 2008

City	Population	City	Population
Kinshasa	7,273,947	Kolwezi	456,446
Lubumbashi	1,283,380	Likasi	367,219
Mbuji-Mayi	1,213,726	Tshikapa	366,503
Kananga	720,362	Kikwit	294,210
Kisangani	682,599	Mbandaka	262,814
Bukavu	471,789		

Source: UN (2009).

Figure 2. A political reference map

Old provinces —— New provinces —— Territories ——

For a more disaggregated measurement of rural and urban populations, we identify the nearest city and its population size using the Global Rural-Urban Mapping Project (GRUMP) population data from the Center for International Earth Science Information Network (CIESIN).[2] These population counts for the year 2000 were adjusted to match United Nations (UN) totals, and the resulting population estimates for territories (the fourth tier of government in the DRC) are presented in Figure 3.

[2] Specifically, it is the Gridded Population of the World, Version 3, with Urban Reallocation (GPW-UR).

Figure 3. Total population by territories

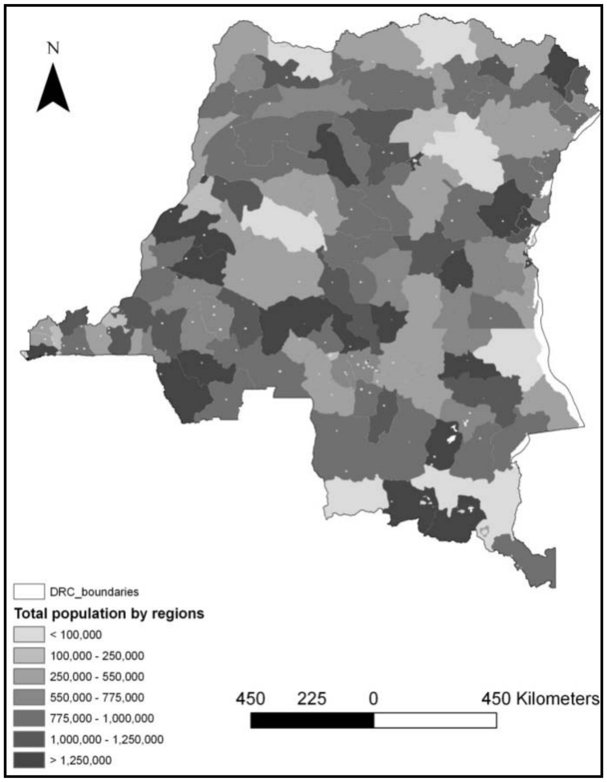
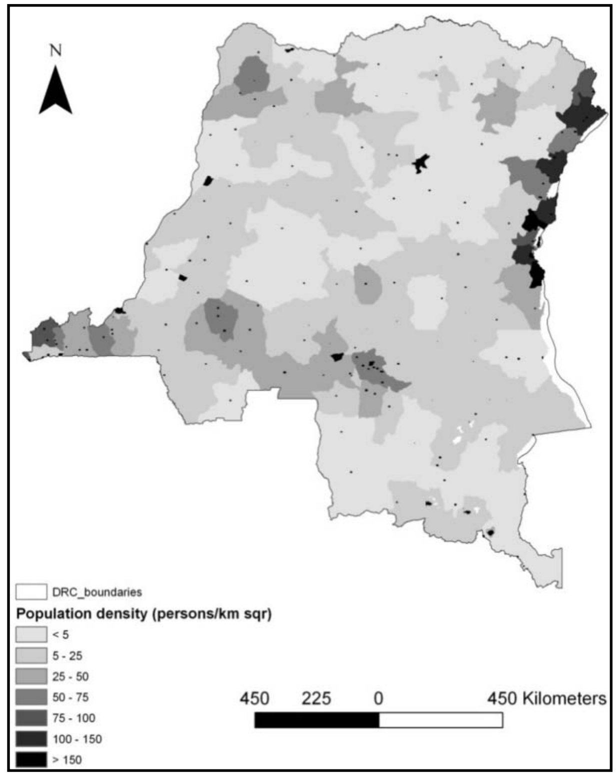


Figure 4. Population density



We then combined friction grids and the locations of cities with different sizes, and calculated travel time to the nearest town or city of (i) 50,000 people or more, (ii) 100,000 people or more, and (iii) 200,000 people or more. For the details, see Thomas (2007).[3] In addition to defining markets on the basis of town or city size as we do below—e.g., 50,000- or 100,000-person towns—we also follow Dorosh et al. (2009) in considering local market size, since this may also influence crop production. There is no consensus on defining the boundary or size of local markets (or a market potential measure), but a standard method is to use a distance decay model in which the weight attached to population aggregates decay as distance increases.[4] Thus, local market size is calculated as:

$$\text{local market size}_{\text{i}} = \sum_{k} w_{k,i}\, pop_k \qquad (1)$$

where pop_k is the population aggregate in neighboring area k and the distance weight is $w_{k,j} = 1/(d_{k,i})^{\gamma}$ where $d_{k,i}$ is the Euclidean distance between k and i in kilometers and γ is an arbitrary decay parameter. Following Dorosh et al. we use two proxy variables: (i) a population count in its own pixel and (ii) a distance-weighted population aggregate in neighboring areas within a 100-kilometer radius (excluding its own population). We divide these areas into six subgroups (radius 1–2 km, 2–5 km, 5–10 km, 10–20 km, 20–50 km, and 50–100 km). The input data are from the GRUMP population counts in year 2000 at 1-kilometer resolution.

Figure 4 shows our results. As expected, population density in the DRC is extremely low, with much of the country being characterized by the lowest two categories of density (less than 25 people per square kilometer). The densest populations are found in North and South Kivu and Ituri in the east of the country, and in and around Kinshasa in the west. Population density in parts of Bandundu, Equateur, and Kasai is also moderately high.

[3] Details of the calculations for Mozambique are given in Dorosh and Schmidt (2008).
[4] See Deichmann (1997) for a review of the issues related to this methodology.

2.2. Estimating Agroclimatic Crop Suitability

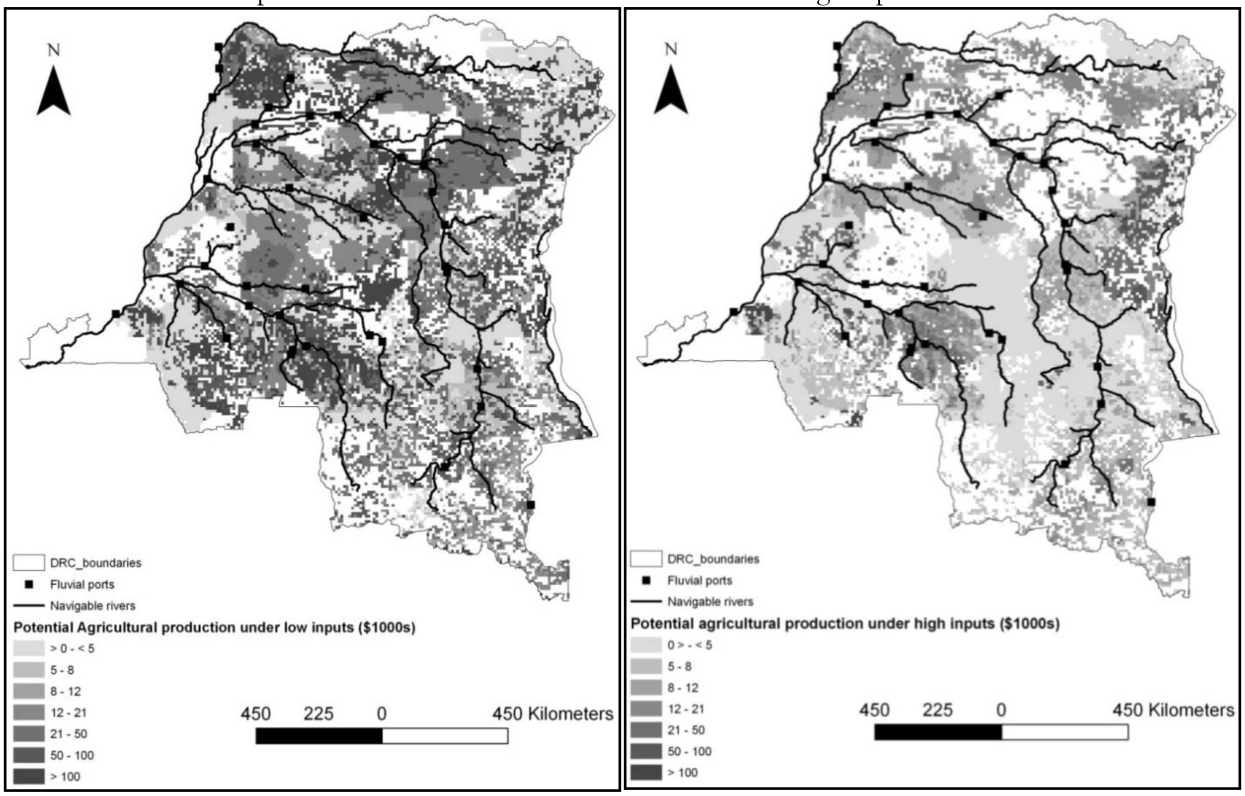
Different crops have different thermal, moisture, and soil requirements, particularly under rainfed conditions. The Food and Agriculture Organization of the United Nations (FAO), with the collaboration of the International Institute for Applied Systems Analysis (IIASA), has developed the Agro-Ecological Zones (AEZ) methodology on the basis of an inventory of land resources and evaluation of biophysical limitations and potentials. The AEZ methodology provides a standardized framework for the characterization of climate, soil, and terrain conditions relevant to agricultural production. Crop modeling and environmental matching procedures are used to identify the crop-specific limitations of prevailing climate, soil, and terrain resources, under different levels of inputs and management conditions. This methodology also provides maximum potential and agronomically attainable crop yields and suitable crop areas for basic land resource units (usually grid cells in the recent digital databases) (Fischer et al. 2001; FAO 2003).

In this paper we measure potential yields for each of three production systems: irrigated—high input (we simply call it "irrigated"), rainfed—high input, and rainfed—low input. Then for each of the three input levels, we define the land suitability by crop based on four classes: very suitable, suitable, moderately suitable, and marginally suitable. Finally, the potential yield is calculated as the area-weighted average of the above four suitable classes (FAO 1981; FAO 2003).[5] To summarize, the agroclimatic crop suitability of a geographical area is a function of three factors: (1) the production system, (2) the crop mix, and (3) the suitability of the land for that crop mix. An important point to note is that factors (2) and (3) are essentially directly estimated from location-specific data, whereas the production system (1) is not. The potential gross revenue for a crop at a certain location (i.e., a 10 km x 10 km pixel in this paper) is calculated by multiplying suitable area, potential yield, and crop price. As the same location may be suitable for growing multiple crops, we define the potential crop production by summing up the potential gross revenues of all suitable crops at this location. Figure 5 shows such crop potential under both high-input and low-input rainfed conditions. In the DRC, we know that there is very little use of irrigation or modern inputs: FAO data for the pre–civil war period of the 1990s suggest that there were about 0.2 tractors per 1,000 agricultural workers, US$0.20 worth of modern fertilizers per worker per year, and irrigation of just over 0.1 percent of the land area. Hence the most plausible measure of agroclimatic crop suitability is one based on the low-input rainfed technology (Panel A, Figure 5). Figure 5 shows that the areas of highest potential are Kasai Occidental in the south-central part of the DRC and Equateur in the northwest, while there is more moderate potential in Bandundu in the southwest (bordering Kinshasa) and Kivu in the east.

[5] Some crops have many types, such as highland and lowland maize germplasm, subdivided by maturity class. In such a case, the single "maize" crop surface is a composite in which each pixel would use the best variety most suitable for the location.

Figure 5. Potential crop production density in the DRC

Panel A. The low-input scenario　　Panel B. The high-input scenario



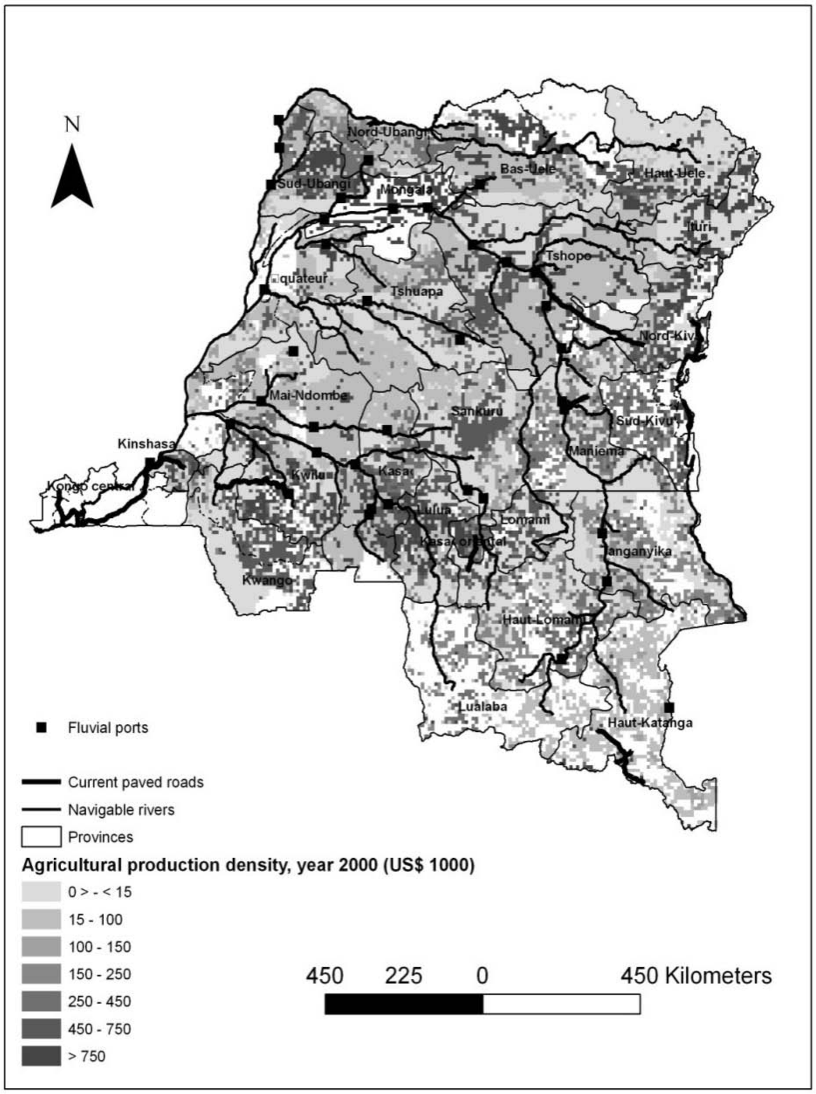
Note: Potential crop production aggregated using individual crop prices (see Appendix Table B.4).

2.3. Estimating the Spatial Distribution of Crop Production in the DRC

In order to evaluate food security, technology potential, and the environmental impacts of production in a strategic and regional context, the International Food Policy Research Institute (IFPRI) has been developing a spatial production allocation model (SPAM) for generating highly disaggregated, crop-specific production data by the triangulation of any and all relevant background and partial information. Here we only briefly and informally describe the spatial allocation methodology. A more detailed description of the technique is presented in Appendix A, while still more complete descriptions of the data sources and the detailed model can be found in You et al. (2007) and You, Wood, and Wood-Sichra (2009). The spatial crop allocation problem is defined in a cross-entropy framework (You and Wood 2006) in which all real-value parameters are first transformed into a corresponding probability form. The objective function of this spatial allocation model is the cross entropy of area shares and their prior, which are subject to a series of adding-up constraints for crop areas, land cover image, and crop suitability information; aggregation constraints between subnational units and irrigation potential; and a simple adding-up constraint for crop shares (Appendix A). The optimization model gives the allocated areas for each 5 x 5 minutes (about 9 x 9 km^2 on the equator). A postprocessing program would take the results from the model and calculate the harvest areas, yield, and production by pixels. The SPAM results also include the subcrop type maps split by production input levels (irrigated, high-input rainfed, low-input rainfed).

Recently, IFPRI released its latest SPAM 2000 data product. These most recent SPAM results represent the last planned major update (Version 3.0) of the global (circa 2000) crop distribution model, which has undergone a significant validation and feedback process involving centers from the Consultative Group on International Agricultural Research (CGIAR) and other collaborators. This release included the following 20 major crops in the world: wheat, rice, maize, barley, millet, sorghum, potato, sweet potato, cassava and yam, plantain and banana, soybean, dry bean, other pulse, sugarcane, sugar beet, coffee, cotton, other fiber, groundnut, and other oil crops. Together these 20 crops account for almost 90 percent of the world's total harvested area. The current paper used an early version of SPAM Version 3. For the DRC, we included the latest (circa 2000) district-level area and production for the following crops: cassava, bean, paddy rice, plantain, sweet potato, millet, and potato.

Figure 6. Estimated crop production density in the DRC



Using the crop distributions from the SPAM model, we first calculated crop production values by multiplying crop production and its corresponding prices. Then we aggregated all crop production values within this pixel to obtain the total production value per pixel. Figure 6 shows our final estimates of crop production values in the DRC. The overall pattern of crop production is not very different from the potential production estimates in Figure 5 (partly by construction), as high-production areas are again observed in the northwest (Equateur), in Bandundu in the west (near Kinshasa), and in southern Kasai. Production is notably estimated to be very low in Katanga in the southeast, and somewhat lower than expected in Kivu in the east, where civil war presumably reduced the agricultural production estimates for 2000.

2.4. Estimating Access to Markets

Lack of access to both input and output markets has been identified as a significant constraint on agricultural development in Sub-Saharan Africa and elsewhere (Ali and Pernia 2003; Minten and Kyle 1999; Jacoby 2000; Van de Walle 2002; Gregory and Bumb 2006; Ahmed and Hossain 1990; Cicera and Arndt 2008; Dercon et al. 2008; Foster 2008). In our modeling exercises we estimated travel times to major cities,[6] airports, and fluvial (river) and maritime ports. In each case, accessibility was estimated using the cost distance function from ESRI,[7] which is defined as the time needed to travel from a specific pixel to the nearest location of interest.

Modeling accessibility required the creation of a friction surface, which represents the time needed to cross each pixel. Speeds both on and off roads are affected by the friction surface, which is integrated by various input layers such as the transport network,[8] land cover (GLC2000 land cover), urban areas (GPW3-GRUMP), slope (derived from SRTM30 elevation), water bodies, international boundaries, and elevation (SRTM30 elevation). The first layer we consider is the elevation and slope, as these are factors that affect both on- and off-road speeds and hence the majority of other infrastructure layers. In effect, then, these factors are used as multiplying factors over the entire friction layer, as per Van Wagtendonk and Benedict (1980):

$$v = v_0 e^{-ks} \tag{2}$$

where v = off-road foot-based velocity over the sloping terrain, v_0 = the base speed of travel over flat terrain, s = the slope gradient (meters per meter), and k = a factor that defines the effect of slope on travel speed.

For the DRC we assume a base speed of 5 kilometers per hour, with k set to 3.0 and constant for uphill and downhill travel. The velocities over the slope grid were computed and then converted into a friction factor by dividing the base speed by the slope speed. This was then used as a multiplier against the other friction components.

When calculating the multiplier for elevation, we assume that elevations lower than 2,000 meters have no effect on travel speed. For elevations above 2,000 meters, the following speed factor is applied:

$$f = 0.15e^{0.0007E} \tag{3}$$

where f is the friction factor and E represents elevation in meters.[9]

Finally, we consider travel times by transport type (e.g., by train or by car). Normally, the approach here assumes the transport types that are common across countries, such that highly detailed maps of transport routes (including road surfaces) suffice to give a good approximation of travel times on the ground (e.g., Nelson 2008; Dorosh et al. 2009). Hence, up-to-date maps are certainly highly important, and we have gone to considerable effort to update our information on road categories (176,000 kilometers), rail networks (1,300 kilometers), and river networks (23,000 kilometers) in the DRC, as well as additional targets such as ports, maritime ports, and national and international airports (fluvial ports are particularly important for the DRC, as the Congo River and its branches are an important transport route for much of the population).

However, it is still not clear that even these updated maps give a sufficiently accurate picture of the situation on the ground. As Minten and Kyle (1999; hereafter MK) note about the DRC:

> Most of the road network is in bad condition, with important sections almost impassable and access to some interior areas severely curtailed. Rural roads are maintained by local authorities who have neither the resources nor the organizational capacity to carry out the task.

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[6] Major cities include Kinshasa and cities with populations equal to or greater than 50,000, 100,000, and 200,000.

[7] For more details about the cost distance algorithm, refer to http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=How%20Cost%20functions%20work (accessed February 21, 2009).

[8] GIS data about road infrastructure, water bodies, hydrography, sea ports, and airports were obtained from http://rgc.cd/index.php (accessed May 28, 2009)

[9] To perform various market access scenarios and to speed up data processing, we used the Python geoprocessing scripting language to run geoprocessing operations and automate processes that include setting geoprocessing environments, reclassifying variables, extracting attributes, and performing advance spatial analyses.

In other words, a road might look normal from a satellite picture or transport map but in reality be "almost impassable." To minimize this error—which could potentially bias our results—we use transport survey data collected by MK for the early 1990s to incorporate travel times into our market access estimates that more clearly reflect the realities on the ground in the DRC. Among other things, the MK survey asked agricultural traders in Kinshasa about where they imported food from and how long the journey took. For each journey MK also distinguished between travel times on paved and unpaved roads. From that data we can obviously derive travel speeds by road type. An additional and very context-specific insight from the MK study is that the DRC's lengthy and intense wet season increases travel times by as much as 40 percent.

But although we consider the incorporation of MK's survey data into our estimates a significant improvement over our generic "cross-country" estimates, we must still acknowledge that significant measurement errors undoubtedly remain, as well as the possibility that we still underestimate travel times in the DRC. First, the MK survey was conducted in the early 1990s, so its data are not very up-to-date. However, it is possible that this is not a major problem because economic stagnation and political turmoil have precluded any significant investments in infrastructure. If anything, roads are probably in worse condition now than they were in the 1990s, when they were already in terrible shape. A second problem is that the MK survey considered only travel times to Kinshasa, so most of its data yield information only on travel times in the west of the country. Given that the war in the east (North and South Kivu) may have led to especially rapid deterioration of the road network, it is possible that we underestimate travel times in these parts. Still, the use of territorial and provincial fixed effects should account for this in our econometric work, and all in all we consider the incorporation of the MK data a significant improvement upon the generic estimates of travel times in Africa and elsewhere.

Table 3 shows assumed velocities by transport type for the dry and wet season, while Figure 7 shows the transport network and the resulting estimates of market access in the DRC. Figure 6 shows the paltry length of the paved road network in the DRC, which is presently confined to the road linking Kinshasa to the coast, and a few patches in other parts of the country. In contrast, the navigable river network is vast and is historically linked to population settlements in the DRC, although reports indicate that some parts of the river have become less commonly used because of infrastructure problems and rising fuel costs (see our concluding section for further discussion). As for Figure 7, this suggests that the vast majority of land area in the country has very poor market access. Had we mapped travel times for the wet season, the map would suggest considerably longer travel times.

Table 3. Assumed travel times by road category

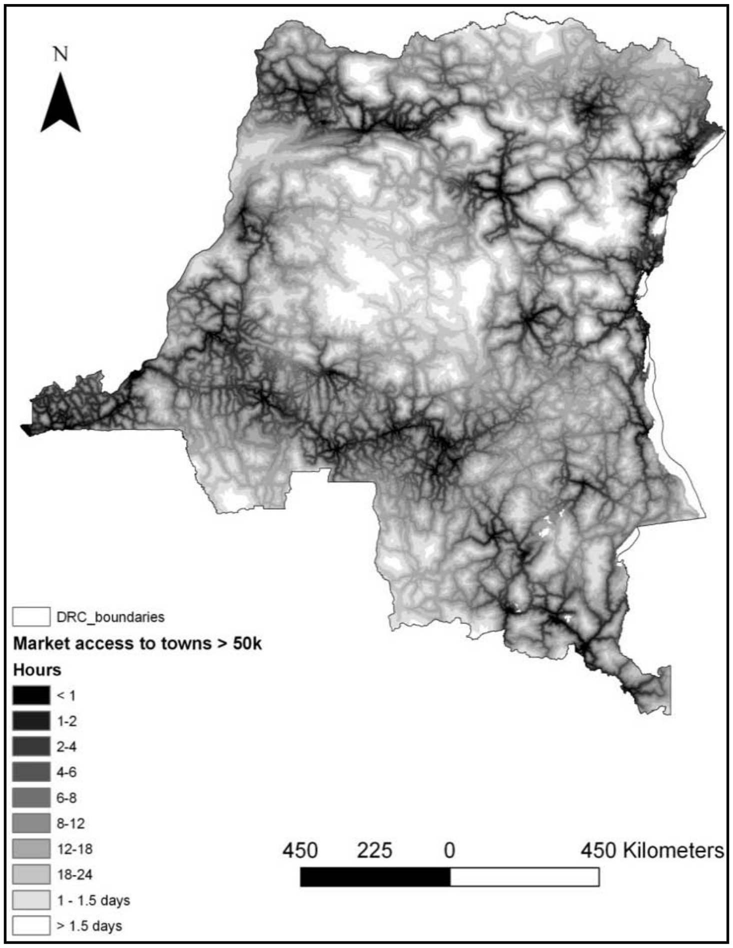
Transport type	Velocity (km/hr) Dry season	Wet season*	Incorporates information from MK's survey?
Paved	80	46	Yes
Four-wheel drive	30	17	Yes
Loose gravel	25	14	Yes
Trail	3	2	
Ferry crossing	5	3	
Rail/train	10	10	
Rivers	10	8	Yes

Source:. Author's calculations

Notes: Speeds are partly based on existing assumptions (e.g., Nelson 2008), partly on anecdotal evidence for the DRC, and partly on Minten and Kyle's (MK's) survey-based estimates of differences in travel times between paved and unpaved roads and between dry and wet seasons.

*Wet season travel time differentials are also based on MK.

Figure 7. Estimates of travel times to 50,000-person towns



Source: Authors' calculations.
Note: See text for details.

3. THE RELATIONSHIP BETWEEN ISOLATION AND POVERTY IN THE DRC

In this section we try to establish what the relationship is between access to markets and general poverty reduction. Travel time, or isolation, has been established as a significant determinant of poverty reduction in a variety of studies, although estimates of the size of the impact do vary substantially. Kwon's (2005) study on the poverty impact of roads in Indonesia finds that road investments improved the performance of provincial economic growth in poverty reduction such that every 1 percent growth in provincial GDP led to a decline in headcount poverty incidence by 0.33 percent in good-road provinces and 0.09 percent in bad-road provinces. Jalan and Ravallion (2002) find that for every 1 percent increase in kilometers of road per capita, household consumption rises by 0.08 percent in poor regions in China. Glewwe, Gragnolati, and Zaman (2000) conclude that rural communes in Vietnam with paved roads have a 67 percent higher probability of escaping poverty than those without. And several studies in the volume edited by Fan (2008) find that rural roads have a very high impact on poverty reduction in places as diverse as China, India, and Uganda. Given the poor state of infrastructure in the DRC, we have a strong presumption that travel time is an important determinant of Congolese poverty, although we also need to bear in mind that other weaknesses in the economy could reduce the advantages of proximity to towns and markets (e.g., poor public service delivery).

Ideally, we would like to establish the impact that agricultural development has on poverty reduction in the DRC, and the interactions between market access, agriculture, and poverty. However, neither of the two substantial household surveys available to us—the Demographic Health Survey (DHS) and the Living Standards Measurement Survey (LSMS)—had agricultural components to them, so linking up agricultural production as a transmission mechanism for infrastructure's effect on poverty in the DRC is not yet possible. Nevertheless, the DHS is useful in that it has what we believe to be a good proxy for travel time to sizable towns or cities, "travel time to the nearest health facility." Moreover, although the DHS is not principally an economic survey, it does contain an asset-based poverty index that has been tested, validated, and strongly advocated by leading development economists (Filmer and Pritchett 2001; Sahn and Stifel 2003). This index is constructed via a principal components analysis of all the available consumer durable and asset variables in the DHS survey, all of which are listed in Table 4.

Table 4. Asset variables used in the construction of the DRC's DHS wealth index

Source of drinking water	Share toilet with other households
Type of toilet facility	Type of cooking fuel
Has electricity	Has bed net for sleeping
Has radio	Has mobile telephone
Has television	Has grill/heater
Has refrigerator	Has chair(s)
Has bicycle	Has bed(s)
Has motorcycle/scooter	Has lamp(s)
Has car/truck	Has stove/cooker
Main floor material	Has hoe(s)
Main roof material	Has sewing machine
Has telephone	Has canoe/dugout

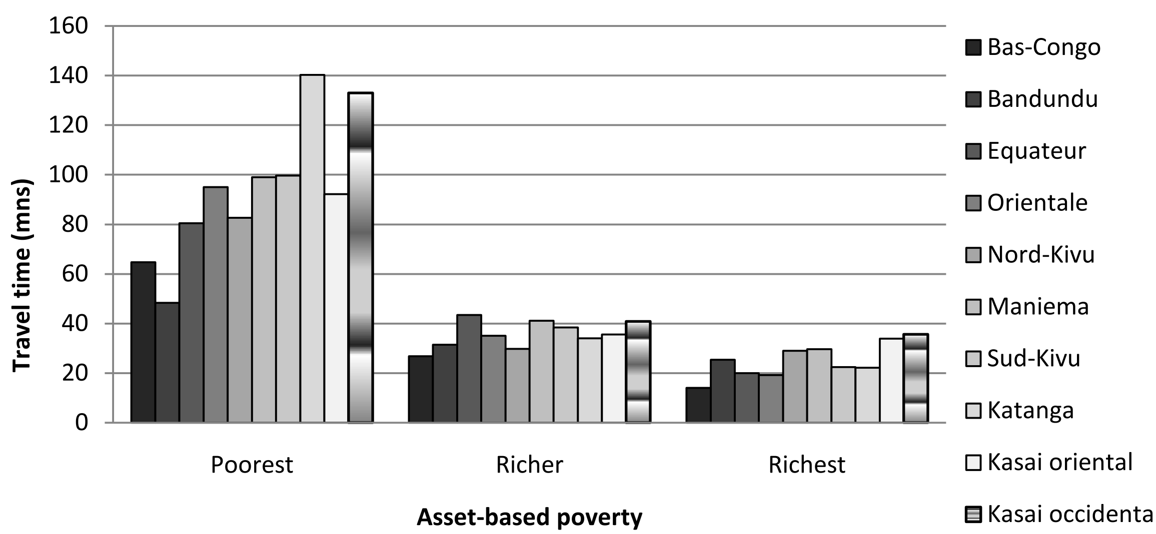
Source: Demographic Health Survey of the DRC (2007).

Although we are confident that each of these measures provides a sufficiently accurate representation of the latent variables—isolation and poverty—there were some technical issues that required careful consideration. First, the asset-based poverty measure may be biased insofar as it could underestimate poverty in urban areas simply because some basic assets are easier to obtain in urban areas. For example, 43 percent of households in Kinshasa—which is an exceptionally poor city by international standards—own a mobile phone, and Kinshasa is the only province in the DRC with substantial electricity supply. Since Kinshasa in particular was a major concern in this regard and in several other regards, we chose to run our wealth regressions separately for each province.

A second issue relates to market access proxy. Health facilities in the DRC are almost solely available in major towns, so it is quite likely that "travel time to the nearest health facility" is a good proxy for travel time to the nearest major town. Still, we must acknowledge potential biases and general measurement error. In terms of biases, it is possible that health facilities are not only urban biased (which is what we assume anyway) but also biased to capital cities or mining towns, and so on. Arguably a more important bias is that access to a health facility influences poverty not through infrastructure or market access per se but through the health facilities themselves. Likewise, access to a city may improve access to education, which in turn affects poverty. In order to more closely capture the effects of access to markets, we therefore run regressions that control for education and health outcomes, as well as other household characteristics such as age and marital status. When education and health are included in the regressions we call this the "market proximity effect," and when education and health are excluded we call this the "total proximity effect."

The full regression results are not reported because running separate regressions for each province results in a large number of results. In Figure 8 and Table 5 we therefore concentrate on the effects of isolation, noting only that the regressions generally seemed to perform well, explaining 20–50 percent of the variation in wealth outcomes across households in a given province. Figure 8 shows the relationship between travel time to health facilities and asset-based poverty within each province. Specifically, we look at the poorest (fifth) quintile, the second quintile ("richer"), and the first quintile ("richest"). Figure 8 demonstrates that with the exception of Kinshasa and neighboring Bandundu Province, the difference in travel times between the poorest and richest Congolese is substantial. In virtually all provinces, an average person in the poorest quintile must travel at least twice as long to reach a health facility as the richest. On this basis, "travel time" looks like a potentially powerful determinant of wealth.

Figure 8. The relationship between travel time to health facilities and asset-based poverty



Source: Authors' calculations based on DHS data.

In Table 5 we report results from more rigorous tests of the impact of isolation on wealth. One issue here is that isolation could impact wealth through a variety of channels, such as access to health goods and services, education, and nonfarm employment, as well as access to other markets, such as agricultural input and output markets. When we run regressions that exclude these variables, we call this elasticity the "total effect." When we run regressions that control for health, education, and agricultural employment outcomes, we call this the "market effect" because the controls presumably net out the other channels through which access to cities affects household wealth. We also think of the difference between both estimates as a rough measure of how important access to agricultural output markets is for household wealth accumulation. Finally, because we are interested in the agricultural population specifically, we also repeat these two specifications for agricultural populations only (clearly, agricultural employment is dropped as a control here). Note, also, that since we are interested in agriculture we drop Kinshasa Province, as it is almost entirely urban.

Table 5 shows that the elasticity between travel time and wealth in the total population varies substantially across provinces—from -0.06 to around -0.40—although the elasticities are significant in all provinces. When we add controls for education, health, and agricultural employment outcomes (Column 2), these market effect elasticities are lower than the total effect in all cases except Kasai Oriental, where the elasticity is about the same. Also, in the two northern provinces of Orientale and Equateur we find that the market effect is zero, suggesting that isolation is not an important determinant of wealth there once education, health, and employment controls are included. These two northern provinces excluded, Column 3 shows that the market effect share of the total effect (Column 2 divided by Column 1) varies from around 50 to 100 percent. Turning next to the agricultural population only—as defined by agriculture being the primary employment of the adult in question—we generally find very similar results. As for why the two northern provinces should not show any market effects, there could be several factors. First, broader market access is very low because there are relatively few major towns and very limited access to Kinshasa. Indeed, river access is the only viable means for any agricultural produce to reach Kinshasa. This largely limits trade to nonperishable goods, and there are also reports that some of the northern river routes are largely unused because of silting and dilapidated port infrastructure.

Of course, the approach adopted to separate total effects from agricultural market effects in Table 5 is fairly crude, and any conclusions we draw from this must certainly be qualified.[10] Also, some (but not all) of the elasticities are rather low. This could due to a number of factors, such as our use of a proxy for market access rather than a more targeted measure (i.e., attenuation bias). Another reason could be the limited purchasing power in urban areas that results from a very depressed economy, and the general unavailability of modern agricultural inputs, such as fertilizers and improved seeds. Nevertheless, Table 5 at least provides some indirect evidence that access to markets could be a very important determinant of wealth accumulation in the DRC, and that isolation constrains wealth accumulation for agricultural workers in particular. In the next section we look to test more specific links between agricultural production and market access.

[10] For one thing, each elasticity is a stochastic point estimate, and we have not tested for differences in elasticities across regressions. Second, it is likely that the estimates of agricultural market effects represent upper bounds, because our ability to control for education and health effects is only as good as the control variables we use, which are doubtless imperfect. Moreover, because our welfare measure is based on specific assets, it may simply be that proximity to towns determines the costs and benefits of purchasing these assets (and repairing them, etc.).

Table 5. Estimated elasticities of travel time and wealth across provinces

	Total population			Agricultural population		
Education, health, and agricultural employment controls included?	No	Yes		No	Yes	
	1. Total effect	2. Market effect	3. Market share = 2/1	4. Total effect	5. Market effect	6. Market share = 5/6
Bandundu	-0.09	-0.05	60%	-0.04	**-0.03***	67%
Bas-Congo	-0.13	-0.12	87%	-0.21	-0.12	57%
Equateur	-0.06	**0.01***	0%	-0.11	**0.00***	0%
Kasai occidental	-0.09	-0.05	61%	-0.13	-0.04	28%
Kasai oriental	-0.09	-0.11	100%	-0.15	-0.09	63%
Katanga	-0.37	-0.35	94%	-0.42	-0.23	55%
Maniema	-0.08	-0.05	57%	-0.07	-0.05	77%
Nord-Kivu	-0.25	-0.22	90%	-0.28	-0.21	74%
Orientale	-0.09	**-0.01***	0%	-0.13	**0.00***	0%
Sud-Kivu	-0.25	-0.11	45%	-0.29	-0.14	47%
Average	*-0.15*	*-0.11*	*61%*	*-0.18*	*-0.09*	*47%*
Average, excluding the north	-17%	-13%	74%	-20%	-13%	59%

Source: Authors' calculations
Notes: * indicates insignificant coefficient at 10% level. "The north" refers to Orientale and Equateur provinces.

4. MARKET ACCESS AND AGRICULTURAL PRODUCTION: WHAT ARE THE LINKS IN THE DRC?

4.1. Conceptual Framework and Model

In assessing the implications of location and transport investments for crop production and productivity in Sub-Saharan Africa, we follow Dorosh et al. (2009) in adopting a conceptual framework in which transport investments affect both the supply of and demand for crop production. On the supply side, the production of crop j under production system l in location (pixel) i depends on the agronomic potential p_j, under the production system l in location i, and unobserved location-specific variables (Ω_i) such as output and factor prices, and available technology. Demand for a crop produced in location i depends on the size of the local market surrounding location i, which is in turn determined by the population, distribution of per capita incomes, and trade regime (especially whether the domestic market is integrated with the international market).

The hypothesis to be tested is that better transport connectivity increases crop production (or productivity) after controlling for other factors. The effects of better transportation are assumed to take place through a reduction in the transport costs of goods and services, which raises the producer prices of crops, as we saw in Section 1. Reduced transport costs also lower the costs and profitability of supplying modern inputs such as fertilizers, seeds, extension services, and other technologies (Ahmed and Hossain 1990). However, because the DRC's agricultural economy currently uses scarcely any of these modern inputs, we suspect that any positive association between market access and agricultural production primarily reflects the impacts of access to output markets for agricultural produce, rather than input markets. Were government policies to simultaneously invest in infrastructure and the adoption of modern inputs, it is probable that the impacts of infrastructure investments would be higher in the long run, although there are many factors in addition to transport costs that explain why African farmers do not adopt modern technologies.

Another way in which greater market access influences agricultural production is by affecting the composition of agricultural production. As lower transport costs result in a greater percentage reduction in the price of perishable and bulky items such as vegetables, the profitability of these items increases relative to nonperishable crops (the von Thunen hypothesis). Indeed, Minten and Kyle (1999) found that this von Thunen effect was very important in the DRC:

> *The more perishable and the higher value the products, such as fruits, vegetables, cassava roots, cassava chikwangue, cassava leaves, tomatoes, pimento, the less distance they are transported. The basic less perishable staples (cassava chips, peanuts, maize) come from further away. The average distance they are transported is 337, 373, and 323 km, respectively. Compared to vegetables, 107 km, they come from three times as far. The von Thunen effect is also illustrated by the smaller standard deviation in distance traveled for the individual products compared to the standard deviation of the average. Only cassava chips and maize are characterized by a higher standard deviation indicating their omnipresence as a cash crop.*

Finally, where the transport cost reduction is large enough and widespread enough, there are potential general equilibrium effects on rural and urban nonfarm sectors, on wages and overall incomes, and on "noneconomic" factors such as political stability and law enforcement. For example, increased agricultural trade boosts demand for transport services in the urban and rural nonfarm economy. However, our model does not capture these spillover effects because we focus only on explaining agricultural production.

Turning more specifically to the impacts of market access on crop production, we closely follow the basic model used by Dorosh et al. (2009), which is a reduced-form crop production function:

$$\text{Crop production}_{ijl} = f(\text{agronomic potential}_{ijl}, \text{local market size}_i, \text{market access}_i, \Omega). \quad (4)$$

Although the measurement of these variables is discussed above, the theoretical rationale for the model is that these variables capture both supply-side factors, such as agronomic potential and access to input markets (although these are not yet important in the DRC), and demand-side factors relating to access to local markets as well as major towns or cities. With regard to the latter, we consider a 50,000-person town a sufficiently sizable market, although we experiment with urban agglomerations of other sizes as well.

4.2. Econometric Issues

Several econometric issues arise with such a model. First, it is necessary to correct for the bias in the regression estimates arising because the dependent variable (crop production/productivity) is left-censored data (i.e., by definition, their values are never less than a certain value, in this case, zero). To overcome this potential bias, we estimate the equations using a Tobit (censored regression) model and drop areas (pixels) that are unsuitable for agricultural production from our regression.

A second broad issue is endogeneity. There are potentially three sources of endogeneity in the methodology outlined above. First, since the dependent variable is a constructed variable, we may have induced endogeneity by construction. Essentially, our approach to generating spatially disaggregated data involves taking the lowest possible subnational data (in the DRC this is at the territorial level) and then plausibly "spreading out" this data across even more disaggregated spatial units (the pixel level) using other spatially disaggregated variables such as land area, rainfall, soil quality, and population. It follows that omitting these variables from our regression could create a serious endogeneity problem because they may affect both agricultural production and market access. We therefore include these variables in all our regressions and experiment with nonlinear specifications as well.

Second, road placement could be endogenous because roads are not randomly allocated across a country. Decisions on where to build roads could be affected by the existing population distribution, geographical factors (e.g., the roughness of the terrain, access to waterways, climate), economic factors (e.g., mineral deposits, land productivity), or political factors (e.g., clientelism, differences in governance quality). Hence, while we may think we are estimating the impacts of market access on productivity, other factors that are correlated with market access could, in fact, be driving the association between market access and agricultural production (generally, we would expect the market access coefficient to be biased upward), leading to spurious regression. However, since we include both province-level and territory-level fixed effects, we argue that our model should adequately control for these factors, assuming they are indeed fixed effects. We also reiterate that our model controls for agricultural potential and population, in case roads are intentionally built to access high-potential or high-population areas. Fixed effects should also control for other factors that are not, strictly speaking, fixed effects, such as conflict in the Kivu region from 1998 onward.

Third, people placement could be endogenous. For example, it is possible that more entrepreneurial farmers might migrate to areas that have better access to roads or larger markets, or to cities. Or refugees from conflict zones might migrate to more isolated areas where land availability is greater (Jacoby and Minten 2009). In the first case, the coefficient on our market access measures could again be biased upward because we would be partially capturing the effects of entrepreneurship rather than pure market access effects. In the refugee case it seems likely that the coefficient could be biased downward.

Without household data it is not possible to purge the market access variable of entrepreneurship or refugee effects, or to know whether there are significant differences between migrant and nonmigrant households in terms of production factors, human capital, farming experience, and so on. However, there are good grounds to think that this bias is probably very small. For one thing, the available evidence suggests that, as a proportion of the total population, migration flows in the DRC have been relatively small. For example, UN data suggest that the total population that migrated out of the DRC from 1950 to 2000 was just over a million. Relative to the DRC's population, that figure is very small. As for internal migration, anecdotal evidence suggests that is also relatively small scale. Rural-to-rural migration is significantly constrained by ethnic and linguistic differences, and generally unnecessary given the abundance of adequate land in the DRC. This mostly leaves rural-to-urban migration, which has been more significant. Although we do not have data on the extent of rural-to-urban migration, we can infer some broad magnitudes from UN data on city sizes in the DRC. Like cities in other African countries, DRC cities have grown quickly from very small bases, but this is partly because of very high fertility rates. Overall, the estimated share of the population that is urban has increased from 19 percent in 1950 to just over 30 percent in 2005. Moreover, these high population growth rates have led many rural towns in the DRC to grow into "urban agglomerations." In other words, the vast majority of Congolese still live where their grandparents lived. Hence, we believe self-selection issues related to migration are a very small bias in the current exercise, although they may have some impact in influencing results for Kivu and other conflict-affected regions.[11]

Another issue related to estimation biases is the use of a cross-section to make projections about the likely impacts of current infrastructure policies. The use of a cross-section essentially implies that we are inferring the long-run benefits of additional infrastructure. In practice, we don't know how long the long run is. For example, suppose that a benefit of being closer to a city is greater access to fertilizers and improved seeds. If farmers lack knowledge of fertilizers and new seeds, their learning process may be quite slow. This example also illustrates that the impacts of new roads are likely to be highly conditional on other policies and outcomes. For example, Ruijsav, Schweigman, and Lutz (2004) demonstrate that the returns to road investments in Burkina Faso are highly conditional upon raising farm productivity and reducing other transaction costs. Urban income growth will also affect demand for agricultural produce. Ruijsav Schweigman, and Lutz also demonstrate that improving only some key roads can have unintended negative consequences for farmers and traders not connected to the new roads because their own goods and services suddenly become less competitive. However, new roads can create new and unexpected opportunities for trade that are not captured in short-run estimates of the returns to roads. Simulation studies have shown that improving roads could lead to more rapid migration, with potentially ambiguous effects on agricultural production and rural and urban welfare (Dorosh and Thurlow 2009). Unfortunately, it is impossible to investigate these rather nuanced effects in our relatively simple econometric approach. Nevertheless, these caveats should be borne in mind, especially when considering the likely impacts of the road investments recently proposed in the DRC.

4.3. Descriptive Statistics

Table 6 presents descriptive statistics aimed at demonstrating some basic results for the key variables of interest. Pixel sizes are roughly 1 square kilometer, so the total sample for the regressions is very large—roughly 25,000—although we use only about 15,000 pixels in the regressions because many pixels do not have crop production values.

Table 7 shows the correlation matrix between the explanatory variables. Initially we were interested in testing a range of market access variables, but mutlicollinearity proved to be serious problem. However, the two most important market access variables for agricultural production in the DRC are access to cities and access to fluvial ports. Minten and Kyle (1999), for example, find that about two-thirds of agricultural trade from the hinterland to Kinshasa is by road, and the other third by river. Moreover, as we saw in the previous section, nearly all the DRC's towns with 50,000-plus populations are located on navigable rivers. The good news is that travel time to a town with 50,000-plus population and travel time to a fluvial port are not so highly correlated that multicollinearity becomes overly serious ($r = 0.61$). The only other variable that is highly correlated with travel time to a city (50,000 or 100,000) is the population of the pixel ($r = -0.46$), indicating that population density decreases with isolation from cities, as expected.

[11] Another issue is whether it is only entrepreneurial people who migrate. Relative to other countries, it is possible that more migration in the DRC is due to conflict, hence reducing the bias due to entrepreneurial migration.

Table 8 looks at these relationships in greater detail by breaking up travel time to a 50,000-person city by deciles (Column 1). Column 2 shows the average travel time in the dry season for each decile. What is most astonishing is the absolute length of travel times. Even the second and third deciles involve travel times of well over five hours (a common benchmark for proximity), while the lower five deciles involve travel times from half a day to an extreme 1.5 days to reach a 50,000-person town. Column 3 also shows that these are not small populations living in isolation.

The bottom five quintiles contain about 25 percent of the total population and involve travel times of half a day or more to 50,000-person towns. As for agricultural production (Columns 4 and 5), most of this takes place in the less isolated regions. About 62 percent of production value takes place in the first four travel-time quintiles. Finally, Column 6 shows production as a percentage of potential production (based on the crop suitability measure described above). This ratio is very low (5 percent or less) for all degrees of isolation, but it also declines almost monotonically with isolation, suggesting that lack of market access is a significant constraint on the fuller utilization of the DRC's agricultural potential. Based on these basic descriptive statistics, we do expect a reasonably strong correlation between market access and agricultural production.

Table 6. Descriptive statistics

Variable	# of observations	Mean	Standard error	Minimum	Maximum
Accessibility (minutes)					
50K cities	24,955	1,008.9	632.4	0	4,397
100K cities	24,955	1,093.1	652.1	0	4,400
Fluvial port	24,955	1,081.9	646.1	0	4,165
Population	24,955	2,273.8	16,697.0	0	1,234,168
Agricultural potential (US$1,000,000)					
Low inputs	24,955	15.0	15.6	0	99
Intermediate inputs	24,955	155.0	178.0	0	1,080
High inputs	24,955	267.0	168.0	0	720
Estimated agricultural production (US$1,000)					
Low inputs	24,955	57.2	160.9	0	3,068.392
Intermediate inputs	24,955	0.1	0.2	0	7.251575
High inputs	24,955	7.0	21.6	0	1,960.588

Source : Authors' calculations

Table 7. Correlation matrix of explanatory variables

	Travel time – 50K city	Travel time – 100K city	Travel time – fluvial port	Potential production	Population
Travel time – 50K city	1.00				
Travel time – 100K city	0.93	1.00			
Travel time – fluvial port	0.61	0.54	1.00		
Potential production	-0.01	0.01	0.11	1.00	
Population	-0.46	-0.46	-0.25	-0.07	1.00

Source: Authors' calculations

Table 8. Travel time, population, and crop production in the DRC

1. Travel time decile	2. Travel time (African average)	3. Percentage of population	4. Production (US$1,000)	5. Production (% total)	6. Production (% potential)
1	3.3	41.4	444.6	19.5	5.4
2	6.7	14.0	401.9	17.7	1.7
3	9.1	9.9	322.5	14.2	2.7
4	11.4	7.1	249.4	11.0	0.3
5	13.7	6.5	179.0	7.9	1.7
6	16.2	5.6	186.8	8.2	0.4
7	18.9	4.7	155.7	6.8	0.2
8	22.3	4.3	130.8	5.7	0.3
9	27.0	3.4	118.3	5.2	0.1
10	39.5	2.9	87.7	3.9	0.1

Source: Authors' calculations

Compared to average crop yields in Africa, the DRC is still lagging behind despite its favorable agroclimatic conditions. For example, in 2006, DRC farmers produced 7.9 tons per hectare of cassava on average, compared to 9.9 tons per hectare in Africa. Of all 149 territories, only 6 (Oshwe, Mwene-Ditu, Kiri, Kamiji, Kabinda, and Inongo) produce above the African average. The yield for rice in Africa (2.3 tons per hectare) is 2.9 times higher than in the DRC (0.78 ton per hectare). The average maize yield (0.8 ton per hectare) is still very low compared to the African average (1.7 tons per hectare).

Using a typology of Congolese territories with respect to the value of agricultural production and travel time to cities of at least 50,000 people, we define four groups of territories: Zone I: low production and high accessibility; Zone II: high production and high accessibility; Zone III: high production and low accessibility; and Zone IV: low production and high accessibility. In terms of road investment priorities, territories in Zone III should be considered as a prime target. Similar conclusions can be drawn with respect to production potential, where 32 territories are above production potential average but below accessibility average.

Table 9 looks to test this hypothesis in a multivariate setting by estimating the supply-and-demand crop production outlined in equation (4) in Section 4. For all regressions we use the Tobit regressor to address the censoring of values. Because both dependent and independent variables are in logs, the censoring is not especially important, but it still accounts for missing values generated by zero production across pixels. Also, all regressions include territorial fixed effects. These territories are the smallest subnational units and number about 150 (some drop out because of limited observations). We also experimented with district fixed effects (of which there are about 30) and provincial fixed effects (about 15). These made no substantial differences to the results, although we tended to find that parameter heterogeneity was more of an issue with these more aggregated fixed effects. In other words, interactions between travel time and crop potential and travel time and population became significant when we stopped using the more disaggregated territorial effects. Those results are not reported here but are available upon request.

Turning to the results in Table 9, we first specified a simple log-linear that is quite similar to the models specified by Dorosh et al. (2009), with the only difference being that we include only pixel population rather than neighboring populations. This was because mutlicollinearity between the pixel population and the local (squared 100 kilometer) population was very high in our sample, so much so that it prevented us from specifying both variables (however, in other results reported below we address this issue through other means). Regression 1 indicates that the elasticity between travel time to a city with 50,000-plus population and agricultural production is highly significant and equal to about -0.44, indicating that a 1 percent reduction in travel time would increase agricultural production by almost 0.5 percent. This is reasonably large, although the elasticity is still much lower than the analogous elasticities reported by Dorosh et al. for all of Sub-Saharan Africa and subregions. The elasticity for agricultural potential is also quite low (0.18), although this is not surprising in a country where agricultural production is highly depressed.

In Regression 2 we depart from Dorosh et al. (2009) by specifying a quadratic term for pixel population, which is highly significant, indicating that the effect of population size on production was generally negative but that the impact declined as population size increased. However, it is somewhat difficult to know what impact this is picking up. Population size could reflect local market access, but it also picks up the size of the labor force (which ought to make the coefficient positive), or available land per capita (average farm size). It could also be that the coefficient is negative because highly dense areas are largely nonagricultural. For these reasons we do not focus much attention on the population term.

In Regression 3 we add a new variable: travel time to fluvial ports. As we saw in Section 2, fluvial ports are extremely important in the DRC because the population has historically agglomerated on these rivers for the benefits that accrue in terms of trade, transport, and water supply. It turns out that the decision to consider fluvial ports in this study was very important. In fact, adding this target significantly reduces the elasticity on market access to towns with 50,000-plus populations—from around -0.43 in Regressions 1 and 2 to just -0.16 in Regression 3. In contrast, the elasticity between travel time to fluvial ports and crop production is around 0.37. In Regression 4 we drop travel time to cities with 50,000-plus populations to see whether fluvial port access might simply be picking up the effect of 50,000-plus towns. However, the coefficient on fluvial ports is substantially larger in Regression 4 than the coefficients in Regressions 1 and 2, so it appears that access to fluvial ports has a genuinely large effect on production. This is not surprising insofar as connecting a farmer to one river port obviously connects him or her to other river ports. Moreover, every river port in the DRC directly connects to the country's largest city (Kinshasa) and the country's only international (maritime) port (Boma). In terms of sheer physical access to population centers, then, the river network has great potential. We therefore take up the question of the river network's trade potential in our concluding section. Finally, Regressions 5 to 7 replicate Regressions 1 to 3, with travel time to towns with 100,000-plus populations replacing travel time to towns with 50,000-plus populations. However, the results are materially the same, with just some slight reductions in elasticities.

Finally, Table 10 compares our results to those of Dorosh et al. (2009), in which the authors run similar agricultural production regressions for Sub-Saharan Africa as a whole as well as West Africa, the region that is most similar to the DRC in terms of agroclimatic factors and crop mix. The first three columns also report results from alternative aggregations of fixed effects. In the DRC sample, we do not find that using alternative aggregations of fixed effects makes any substantive difference to the results. However, the main finding in Table 10 is that the elasticities for market access and crop potential are much smaller in our DRC sample than they were in the full African or West African samples used by Dorosh et al. One concern is that the Dorosh et al. study uses very limited country effects, which could conceivably lead to some upward bias in the results (for example, if fixed effects simultaneously account for both greater market access and greater production levels), but we have no way of confirming this, and we should also note that the disparities could well be real. Indeed, one problem we face in this study is that every element of the DRC economy—the infrastructure and agriculture sectors in particular—is so depressed that the elasticities in Tables 9 arguably do not reveal the true potential of agriculture in the DRC (see our concluding section for more discussion of this issue).

Table 9. Estimating the impacts of road connectivity on crop production (log)

Regression No.	1	2	3	4	5	6	7
Estimation method	Tobit	Tobit	Tobit	Tobit	Tobit	Tobit	Tobit
Ln(travel time to 50K city)	-0.44***	-0.43***	-0.16***				
Ln(travel time fluvial port)			-0.37***	-0.51***			-0.43***
Ln(travel time to 100K city)					-0.43***	-0.41***	-0.10**
Ln(potential production, low inputs)	0.18***	0.18**	0.18***	0.18***	0.18***	0.18***	0.18***
Ln(population)	-0.05**	-0.43***	-0.45***	-0.50***	-0.05*	-0.43***	-0.46***
Ln(population), squared		0.027***	0.027***	0.033***		0.027***	0.030***
Total observations	15,122	15122	15122	15125	15125	15125	15125
Pseudo R-squared	0.084	0.084	0.085	0.085	0.083	0.083	0.085
Territorial fixed effects	yes	yes	yes	yes	yes	yes	yes

Source: Authors' calculations
Notes: * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 10. Comparing across alternative fixed effects and samples

Source of elasticities >>	DRC	DRC	DRC	Dorosh – All Sub-Saharan Africa	Dorosh – West Africa
Fixed effects	Territories	Districts	Provinces	Countries	Countries
No. of fixed effects	150	30	15	42	5
Total observations	15,525	15,525	15,525	125,982	15,500
Ratio (%) of fixed effects to no. of observations	0.97	0.19	0.10	0.03	0.03
Elasticities					
Travel time to 100K-plus city	-0.43***	-0.46***	-0.41***	-2.864***	-1.102***
Crop potential	0.18***	0.22***	0.20***	0.247***	0.406***

Source: Authors' calculations

Finally, in addition to the robustness tests involving fixed effects, we also engaged in one other potentially important robustness test. Instead of specifying total crop production as the dependent variable, we specified total production per capita. Although the pixel populations are no doubt measured with considerable error (there has not been a census in the DRC since the 1980s), production per capita is a variable that ought to have a closer connection to rural welfare (i.e., incomes, food security) than total production, which is more important from a trade perspective. The results are reported in Appendix Table B.1. The per capita production regressions in Appendix Table B.1 also include a new explanatory variable—local population density—which is used as a proxy for local market access in the Dorosh et al. (2009) study. However, as in the Dorosh et al. results for low-input African agriculture, we find that the elasticity of this variable is negative. We suspect that this is because higher local population densities may be capturing smaller farm sizes and the greater prevalence of nonfarm activities. Again, we can attach only very limited importance to these results. The more important finding from the robustness tests in Appendix Table B.1 is that the per capita elasticities for market access and crop potential are very similar to those reported in Table 9.

5. SIMULATING THE IMPACTS OF PROPOSED ROAD INVESTMENTS IN THE DRC

In the introduction we noted that the World Bank and the British government have signed a five-year agreement for the rehabilitation and upgrading of 1,800 kilometers of high-priority roads, while China and the DRC government are planning to rehabilitee some 5,800 kilometers of roads and an equally long railway network. Since one of the motivations for this paper is to provide an agricultural perspective on forthcoming infrastructure investments, this section presents estimates of the impact of alternative road investment plans on market access and agricultural production. To do so, we calculate market access with respect to three scenarios:

1. The "government's plan": pavement of 8,500 kilometers of roads and the construction and improvement of railways. This includes the government's major road programs with funding and assistance from the World Bank, the British government, and the Chinese government. The upgraded road areas are listed in Appendix Table B.2.
2. Our own "network plan": pavement of 10,193 kilometers of national roads, resulting in a more ambitious road network that creates a contiguous pan-DRC network linking the four corners of the country.
3. A "comprehensive plan": pavement of 10,193 kilometers of national roads to create a contiguous pan-DRC road network, plus the upgrading of 26,000 kilometers of feeder roads, which (by assumption) involves changing the average speed from 30 kilometers per hour to 50 kilometers per hour. This is a very ambitious plan involving greater integration of the rural community.

Table 11. Scenarios by road category

	Transport category (km)						Estimated cost of each plan (US$ millions)
	Paved roads (80km/hr)	4WD roads (30km/hr)	Loose gravel (25km/hr)	Trails (walking) (3km/hr)	Ferry crossing (5km/hr)	Ferries, boats, etc. (10km/hr)	
Current network	1,611	26,500	59,500	87,200	239	1,486	n.a.
Future scenarios							
"Government's"	8,500	25,875	53,236	87,200	239	3,200	US$2,064
"Network"	10,193	26,074	51,344	87,200	239	3,200	US$3,053
"Comprehensive"	10,193	26,074 (80 km/hr)	51,344	87,200	239	3,200	US$3,461

Source: Authors' simulation assumptions.
Notes: The government's plan is based on World Bank, U.K. Department for International Development (DFID), and Chinese government documents. Please contact the authors for further details. The estimated cost of each plan is based on Africon (2008). See text for details.

Table 11 describes each scenario by road category, while Figures 9 to 12 present the geographical distribution of roads included in each scenario. The last column of Table 12 also estimates the costs of each project based on a recent study conducted by Africon (2008) for the Africa Infrastructure Country Diagnostic (AICD). The paper assessed the unit costs of road construction for 115 road projects in Africa (mostly funded by a single donor), including 25 contracts to build new paved roads, 45 to rehabilitate paved roads, 8 to maintain paved roads, and 37 to regravel unpaved roads. To estimate the costs of each of the scenarios in Table 12 we used the median cost of rehabilitating paved roads (US$299,551 per lane kilometer) to speeds greater than 50 kilometers per hour, and the median unit cost of regraveling roads (US$15,625 per lane kilometer). Although the derived figures are consistent with the sums of money being proposed by the World Bank, DFID, and China, the estimates are only ballpark figures, so the real costs could be substantially higher or lower. They could be lower because (1) the Africon report found that the lower quartile unit costs for paved roads rehabilitated were just two-thirds that of the median level (US$194,679); (2) the median values were significantly higher than unit costs reported by the World Bank (one of the donors in the DRC); and (3) unit costs tended to be lower for larger projects (which the DRC's certainly is), presumably because of economies of scale. However, the report also found that unit costs of road infrastructure projects in Africa have been rising in recent years due to rising costs of materials and fuel, sometimes by as much as 30–50 percent. Moreover, it seems reasonable to expect that the DRC's difficult terrain and climatic conditions could mean that road construction there is more expensive than normal.

Simulation results suggest that the government roads program will reduce travel time to fluvial ports and nearest cities with at least 50,000 people by 10.7 and 10.9 percent, respectively (Table 12). Interestingly, however, there is a great deal of variation by province and by whether fluvial ports or general town access is considered. For fluvial ports, two provinces are expected to see travel times reduced by around 20 percent: Nord Kivu and Province Orientale. This is consistent with the fact that a number of fluvial ports are located in Province Orientale. But for access to towns with populations of 50,000, the dispersion across provinces is more limited. As for the network plan, we surprisingly find that its impacts seem to be similar to those of the government plan, reducing travel time to ports by 11.0 percent but only reducing travel times to cities by 10.1 percent. More interesting are the effects of the comprehensive plan, which includes an upgrading of rural feeder roads. Upgrading these feeder roads almost doubles the reduction in travel times.

Figure 9. Current paved roads

Figure 10. Government upgrade program

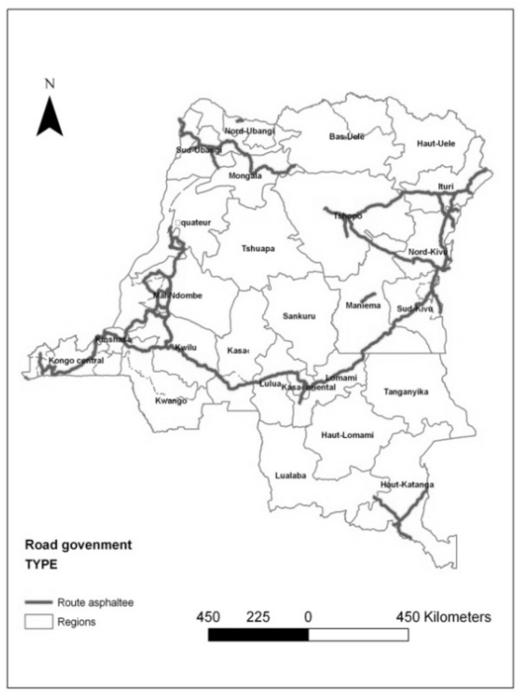


Figure 11. Pan-DRC network plan

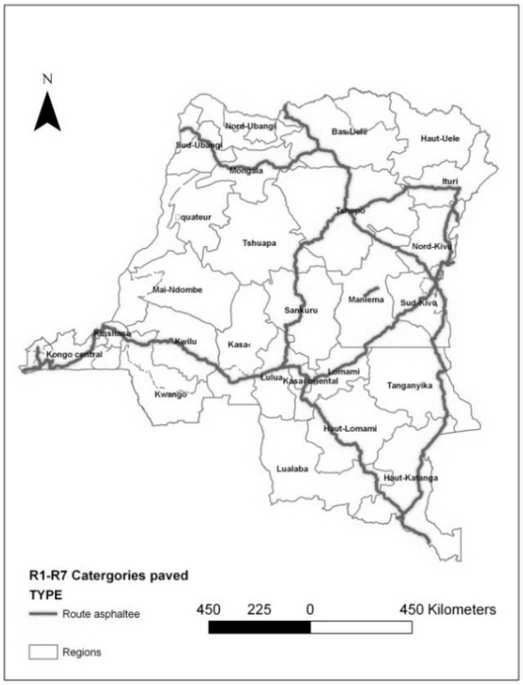
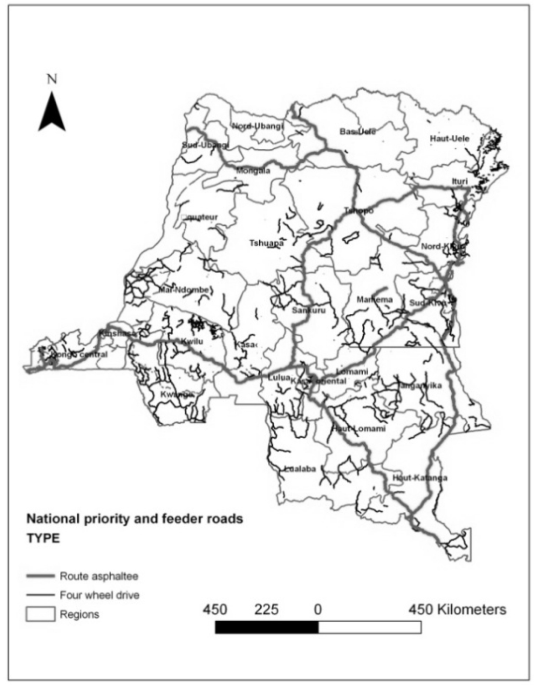


Figure 12. Comprehensive plan with rural feeder roads



Source: Maps derived by the authors.

Table 12. Impact of road investments on travel times by scenario (% change)

	Fluvial ports			Nearest 50,000-person cities		
Province	Government	Network	Comprehensive	Government	Network	Comprehensive
Bandundu	-8.1	-5.4	-17.8	-7.8	-5.0	-18.0
Bas-Congo	-13.5	-0.7	-8.0	-18.1	-0.8	-11.2
Equateur	-5.8	-4.1	-10.4	-11.8	-8.2	-16.0
Kasai-Occidental	-5.1	-6.8	-15.8	-7.6	-10.8	-19.6
Kasai-Oriental	-1.9	-13.7	-21.6	-6.1	-19.1	-25.2
Katanga	-12.5	-13.8	-22.0	-8.0	-8.7	-17.6
Kinshasa	-7.5	-4.9	-5.5	-7.7	-5.1	-5.7
Maniema	-2.1	-1.3	-13.0	-8.7	-7.4	-15.3
Nod-Kivu	-22.4	-17.2	-19.9	-12.2	-9.7	-14.3
Province Orientale	-21.0	-21.5	-26.0	-14.4	-12.8	-19.3
Sud-Kivu	-9.7	-11.4	-21.9	-18.0	-18.7	-23.7
Total	**-10.7**	**-11.0**	**-18.4**	**-10.9**	**-10.2**	**-18.1**

Source: Authors' simulation results.

Table 13 shows the estimated impacts on agricultural production. The first finding is that, regardless of scenarios, the provinces of Province Orientale, Equateur, Kasai-Oriental, and Bandundu capture more than 68 percent of the additional value of agricultural production induced by road investments. Second, the government and network plans are both estimated to boost agricultural production by around US$11 million, while the comprehensive plan would increase production by US$16.6 million, an increase of around 50 percent. This 50 percent increase in production is quite high relative to the extra costs of the feeder roads (just 13 percent). However, the agricultural returns to building roads are fairly small relative to the cost of building the roads, precisely because the estimated elasticities between travel time and production are relatively low in the DRC. Even excluding the costs of road maintenance, 10 years of increased agricultural production would result in US$0.11 billion of extra agricultural production, whereas the costs of the roads would be almost US$2.1 billion. We note, however, that were we to use the estimated elasticities derived by Dorosh et al. (2009), a simple back-of-the-envelope calculation would suggest that the extra agricultural production would add up to around US$0.6 billion (if the Africa-wide elasticity of 2.86 is used) or US$0.23 billion (if the West African elasticity of 1.10 is used).

Table 13. Impact of road investments on agricultural production by scenario (US$ thousands)

Province	Government	Network	Comprehensive
Bandundu	1.9	1.7	2.8
Bas-Congo	0.5	0.0	0.5
Equateur	1.7	1.4	2.3
Kasai-Occidental	0.5	0.7	1.4
Kasai-Oriental	0.3	1.3	1.9
Katanga	0.7	0.7	1.2
Kinshasa	0.1	0.1	0.1
Maniema	0.1	0.1	0.5
Nod-Kivu	0.8	0.6	0.7
Province Orientale	3.7	3.6	4.3
Sud-Kivu	0.6	0.7	0.9
Total	**11.0**	**10.8**	**16.6**

Source: Authors' simulation results.
Notes: Estimates derived by recalculating travel times in the DRC using the elasticities from Regression 3 in Table 9.

6. DISCUSSION

The question of how best to translate the DRC's enormous agricultural potential into an engine of economic growth and poverty reduction is a vitally important one, but a question still significantly underresearched. This paper has argued that infrastructure is probably the most binding constraint on what is a highly dispersed and predominantly agrarian economy; however, our principal goal was to address not the very general question of whether infrastructure is important for the DRC, but how important infrastructure is for agricultural production and poverty reduction. As it turns out, our results also provide preliminary evidence on the effects of specific infrastructure strategies, such as the distinction between access to general towns and access to fluvial ports, as well as on how the placement of roads would affect agricultural production.

Given our strong priors about the importance of agriculture in the DRC, we unsurprisingly find highly significant and negative elasticities between travel times to sizable cities (50,000 or 100,000 population), although we also find that these elasticities are small relative to those of similar cross-country tests (Dorosh et al. 2009). Moreover, city access by itself is less important than access to cities *and* ports. Since this is potentially a very important finding insofar as it provides a partial answer to the "What kind of infrastructure?" question posed above, it behooves us to consider the theoretical merits of this finding in more detail.

There are several significant reasons why access to fluvial ports is so important in the DRC. First, an individual port significantly broadens the scope of the market beyond the port city itself by connecting a farm to other cities through the DRC's vast river network. Indeed, the DRC river network—which extends about 23,000 kilometers—is around 12 times longer than the DRC's paved road network (less than 2,000 kilometers). Second, because of historical patterns of population settlement and the traditional advantages that river trade has in comparison to trade via a very weak road network, well over half of the DRC's 40-odd cities with populations of 50,000-plus lie on one of the navigable rivers (the Congo River). Third, practically all of the rivers in question not only flow into the largest market (Kinshasa) but also into the DRC's only international maritime port.

So given this apparent network scale advantage, it is perhaps not surprising that access to fluvial ports has an even larger statistical association with agricultural production than does city access alone. Nevertheless, the trade potential of the river network is limited by several factors. First, it is obviously not possible for a port on one river to access ports on unconnected rivers, so trade patterns follow the natural course of the river, whereas road networks are far less constrained by such natural barriers. Second, river transport is very slow. According to Minten and Kyle's (1999) findings for average Kinshasa traders, "A complete cycle by road takes 4 days to travel, 3 days to gather and buy the products, and 2 days to sell them while a cycle on the river lasts much longer: 20 days on the river, 10 days for gathering, and 3 days for selling." Moreover, Minten and Kyle's survey revealed that although river transport appears to be about one-third cheaper than road transport, losses for river transport are quite high, presumably because of the long duration of river journeys.

Hence, river travel is suitable only for relatively nonperishable goods. However, one way of increasing the potential for agricultural trade on the DRC river networks could be to promote agroprocessing in river ports. This would not only reduce the perishability of agricultural produce, it would also facilitate employment growth and nascent industrialization. Informal communication with DRC policymakers also suggests that there is considerable scope to reduce river travel times, perhaps by as much as 50 percent. It is beyond the scope of this paper to offer more rigorous evidence on how much weight the DRC government should place on river transport rehabilitation versus road rehabilitation, but several further points are worth mentioning. First, roads and rivers are symbiotic. Even our own results relate to road-based travel times to ports, so we are implicitly exploring this synergy. This should remind us that it is improving the efficiency of the infrastructure network as a whole that is important—improving the road and river networks by themselves and linking them up in better ways are vital means to achieving that goal.

Another question we have not directly touched upon is, "Who will benefit from increased trade and production?" Obviously, if production increases then farmers will benefit, provided that prices do not decline. However, lower transport costs should generally lead to higher prices being paid to farmers (which is a leading factor inducing the production increase in the first place). So the real question is not whether farmers will benefit but how substantially they will benefit. Given how vast the country is, there is not yet enough evidence to comprehensively answer this question, but indicative information is provided by two recent studies on transportation costs in agriculture trade, mostly in western DRC. The first piece of evidence from GRET (2004) relates to the distribution of income along the agricultural value chain. In the GRET study, the authors found that transporters obtain the majority of the income along the value chain, consistent with the very high transport costs observed in the DRC (Table 14). On average, farmers captured just over 20 percent of the overall income for cassava and 27.5 percent for maize.

However, the second study by Rodriguez, Chinamula, and Mboso (2004) uses a comparative approach to show that farmers should substantially benefit from road rehabilitation. Two cities (Kokodia and Kenge) that are both 280 kilometers from the capital city of Kinshasa were chosen in Bandundu and Bas-Congo, two provinces bordering Kinshasa. The city of Kokodia is on the National 1, which has been rehabilitated recently, while Kenge is on the National 2, which is in very bad shape. Because the differences in distance are the same, the difference in road quality will be the primary factor explaining differences in market access. Consistent with this, the study found a 30 percent difference in transport costs between the two locations and Kinshasa and that the price of palm oil, which is much less perishable than cassava and maize, was the same across the two locations. As for the breakdown of the maize and cassava value chains, the study found that although wholesale prices on the Kokodia-Kinshasa route were almost double those of the Kenge route, Kokodia farmers nevertheless received maize and cassava prices that were 50–60 percent higher than those paid to farmers in Kenge (Table 15). On the basis of this evidence, it appears that even though middlemen or wholesalers substantially benefit from improved infrastructure, DRC farmers will also see their incomes increase because of changes in road infrastructure.

Table 14. Shares of income along agricultural value chain in the DRC, 2000–2003

Cassava				Maize			
Transport	Facilitator	Retailer	Farmer	Transport	Facilitator	Retailer	Farmer
45.8%	4.2%	28.8%	21.2%	45.8%	4.2%	33.1%	27.5%

Source: Ministère de l'Agriculture (2006).

Table 15. Differences in agricultural prices and transport costs based on a natural experiment

	Kokodia in Bas-Congo (on paved road)			Kenge in Bandundu (not on paved road)		
	Cassava	Maize	Palm oil	Cassava	Maize	Palm oil
Storage	100	100		100	100	
Handling	200	200	20	200	200	20
Taxes	200	200	50	200	200	50
Other	500	500	100	1,600	1,800	100
Transport cost	1,200	1,200	100	4,000	4,000	100
Farm gate price	*3,000*	*3,200*	*500*	*2,000*	*2,000*	*500*
Wholesale price	5,900	5,900	730	3,000	3,000	730
Sum = retail price	11,100	11,300	1,500	11,100	11,300	1,500
Benefit to farmers	1,000	1,200	0			
Benefit to wholesalers	2,900	2,900	0			
Benefit to retailers						

Source: Rodriguez, Chinamula, and Mboso (2004).

Finally, we looked at the important policy question of how alternative road investments could affect agricultural production. We drew two conclusions. First, among the alternative plans, the plan that includes an upgrading of feeder roads significant raised the rate of returns for agricultural production relative to upgrading main roads only. This is not surprising, given that main roads essentially connect major cities to one another, whereas feeder roads connect rural people to main roads and market towns (Dorosh and Schmidt [2008] find similar results in their study of Mozambique).

However, a second finding is that the returns to agricultural production are very low relative to the costs of the roads. (Of course, this does not mean that the total benefit of roads will not be positive, because obviously much of the return will accrue to the nonfarm sector, especially the transport sector.) This is primarily because of the low elasticity between market access and agricultural production that we estimated for the DRC. Hence, we need to ask why these estimates are lower in the DRC than they are in the rest of Africa. We propose three explanations. First, urban incomes may be much lower in the DRC than in other African countries, thus weakening demand-side effects on agricultural production. Unfortunately, there is no reliable cross-country evidence on urban incomes, but Povcal data for average national incomes do not suggest that the DRC is significantly poorer than most other African countries, and urban poverty rates are certainly very high in Nigeria and other large African countries.

A second explanation is that farmers in other African countries rely more on access to input markets, such as fertilizers and improved seeds. For crops such as cassava and maize in particular, the use of improved seeds is high in most African countries, but seems to be rather low in the DRC. And while chemical fertilizer use is low in much of Africa, it is virtually nonexistent in the DRC. This leads us to conclude that the estimated elasticities between production and market access capture only demand-side effects on agricultural production.

A third reason for the gap may be estimate error. Despite our attempts to derive more country-specific estimates of travel times for the DRC, anecdotal evidence indicates that the state of transport in the DRC is so dire that we could still have substantially underestimated travel times. Many roads may be roads in name only, and there are also substantial problems with the river transport system such that operating boats along large tracts of the system is simply physically impossible or economically unfeasible.

The last point worth making is that the discussion above clearly highlights the fact that the agricultural returns to building roads are very much conditional upon other policies. If government policies can increase extension services and promote the adoption of modern inputs in the DRC, then more vibrant input markets could substantially increase the returns to new roads. If urban incomes continue to rise, then much of this incremental income will be spent on food, thus stimulating demand and opening up further trade opportunities. If agroprocessing facilities can be developed at fluvial ports, then this could greatly increase the scope for trade in nonperishable goods. All these factors should remind us that although roads and other types of infrastructure do indeed pave the way for development, their usefulness very much depends upon the broader economic environment.

APPENDIX A: THE SPATIAL PRODUCTION ALLOCATION MODEL (SPAM) FOR ESTIMATING CROP PRODUCTION

We define our spatial crop allocation problem in a cross-entropy framework (You and Wood 2006). The first step is to transform all real-value parameters into a corresponding probability form. We first need to convert the reported harvested area, $HarvestedArea_{jl}$ for each crop j at input level l into an equivalent physically cropped area, $CropArea_{jl}$, using cropping intensity.

$$CropArea_{jl} = HarvestArea_{jl} / CroppingIntensity_{jl} \tag{A.1}$$

Let s_{ijl} be the area share allocated to pixel i and crop j at input level l with a certain country (say, **X**). A_{ijl} is the area allocated to pixel i for crop j at input level l in country **X**. Therefore:

$$s_{ijl} = \frac{A_{ijl}}{CropArea_{jl}} \tag{A.2}$$

Let π_{ijl} be the prior area shares we know by our best guess for pixel i and crop j at input level l in country **X**. The modified spatial allocation model can be written as follows:

$$\underset{\{s_{ijl}\}}{MIN} \qquad CE(s_{ijl}, \pi_{ijl}) = \sum_i \sum_j \sum_l s_{ijl} \ln s_{ijl} - \sum_i \sum_j \sum_l s_{ijl} \ln \pi_{ijl} \tag{A.3}$$

subject to:

$$\sum_i s_{ijl} = 1 \quad \forall j \, \forall l \tag{A.4}$$

$$\sum_j \sum_l CropArea_{jl} \times s_{ijl} \le Avail_i \quad \forall i \tag{A.5}$$

$$CropArea_{jl} \times s_{ijl} \le Suitable_{ijl} \quad \forall i \, \forall j \forall l \tag{A.6}$$

$$\sum_{i \in k} \sum_l CropArea_{jl} \times s_{ijl} = SubCropArea_{jk} \quad \forall k \forall j \in J \tag{A.7}$$

$$\sum_{l \in L} CropArea_{jl} \times s_{ijl} \le IRRArea_i \quad \forall i \tag{A.8}$$

$$1 \ge s_{ijl} \ge 0 \quad \forall i, j, l \tag{A.9}$$

where:

$i : i = 1, 2, 3, \ldots,$ pixel identifier within the allocation unit, and

$j : j = 1, 2, 3, \ldots,$ crop identifier (such as maize, cassava, rice) within the allocation unit, and

l : l = *irrigated, rainfed—high input, rainfed—low input, subsistence,* management and input levels for crops

$k : k = 1, 2, 3, \ldots,$ identifiers for subnational geopolitical units

J: a set of those commodities for which subnational production statistics exist

L: a set of those commodities that are partly irrigated within pixel i

$Avail_i$: total agricultural land in pixel *i*, which is equal to total agricultural area estimated from land cover satellite images as described in section 2.

$Suitable_{ijl}$: the suitable area for crop *j* at input level *l* in pixel *i*, which comes from FAO/IIASA suitability surfaces as introduced in section 2.

$IRRArea_i$: the irrigation area in pixel *i* from global map of irrigation

The objective function of the spatial allocation model is the cross entropy of area shares and their prior. Equation (A.4) is the adding-up constraints for crop-specific areas. Equation (A.5) is the land cover image constraint that the actual agricultural area in pixel *i* from satellite images is the upper limit for the area to be allocated to all crops. Equation (A.6) is the constraint that the allocated crop area cannot exceed what is suitable for the particular crop. Constraint (A.7) sets the sum of all allocated areas within those subnational units with existing statistical data to be equal to the corresponding subnational statistics. Constraint (A.8) includes the irrigation information: the sum of all allocated irrigated areas in any pixel must not exceed the area equipped for irrigation indicated in the global map of irrigation (Siebert, Döll, and Hoogeveen 2001). The last equation, Equation (A.9), is basically the natural constraint of s_{ijl} as shares of total crop areas.

Obviously, an informed prior (π_{ijl}) is very important for the success of the model. We create the prior based upon the available evidence. First, for each pixel, we calculate the potential revenue as

$$\mathrm{Re}\,v_{ijl} = \mathrm{Pr}\,ice_j \times \mathrm{Pr}\,ice\,\mathrm{var}_{ij} \times Yield_{jl} \times Suitability_{ijl} \times Suitable_{ijl} \tag{A.10}$$

where $Price_j$ and $Yield_{jl}$ are the price index and the average yield for crop *j* at input level *l* (yield only) for the allocation unit (countries in Sub-Saharan Africa), and $Suitability_{ijl}$ is the suitability for crop *j* at input level *l* and pixel *i*, which is represented as a proportion (value between 0 and 1) of the optimal yield. $Pricevar_{ij}$ is the price variability (value between 0 and 1) for crop *j* and pixel *i*. Currently, we use the population density as an approximation for spatial price variation. Then we pre-allocate the available statistical crop areas (at various geopolitical scales) into pixel-level areas by simple weighting:

$$Area_{ijl} = SubCropArea_{jk} \times Percent_{jl} \times \frac{\mathrm{Re}\,v_{ijl}}{\sum_{i \in k} \mathrm{Re}\,v_{ijl}} \quad \forall j \forall i \forall l \tag{A.11}$$

where $Area_{ijl}$ is the area pre-allocated to pixel *i* for crop *j* at level *l*, and $Percent_{jl}$ is the area percentage of crop *j* at input level *l*. For those geopolitical units without area statistics, we simply merge them together and obtain the total area for that merged unit by subtracting the sum of available subnational areas from the national total. After this pre-allocation, we calculate the prior by normalizing the allocated areas over the whole country.

$$\pi_{ijl} = \frac{Area_{ijl}}{\sum_i Area_{ijl}} \quad \forall j \forall i \forall l \,. \tag{A.12}$$

To convert the allocated crop areas into production, we need to consider both the broader production systems and the spatial variation within the systems. We first calculate an average potential yield within spatial units, $\overline{Y}_{jl}$, for crop *j* in production system *l* using the allocated areas (A_{ijl}) as weight:

$$\overline{Y}_{jl} = \frac{\sum_i Suitability_{ijl} \times A_{ijl}}{\sum_i A_{ijl}} \tag{A.13}$$

We then estimate the actual crop yield of crop *j* in production system *l* and pixel *i* (Y_{ijl}) as

$$Y_{ijl} = \frac{Suitability_{ijl} \times Yield_{jl}}{\bar{Y}_{jl}} \tag{A.14}$$

where $Yield_{jl}$ is the statistical yield (from census data) for crop *j* in production system *l*. The production of crop *j* in production system *l,* and pixel *i,* $Prod_{ijl}$, could be calculated as the following:

$$\Pr od_{ijl} = (A_{ijl} \times CroppingIntensity_{j}) \times Y_{ijl} \tag{A.15}$$

APPENDIX B: SUPPLEMENTARY TABLES

Table B.1. Results with the log of crop production per capita as the dependent variable

Regression No.	C1	C2	C3	C4	C5	C6	C7
Estimation method	Tobit	Tobit	Tobit	Tobit	Tobit	Tobit	Tobit
Ln(travel time to 50K city)	-0.37***	-0.35***	-0.04				
Ln(travel time fluvial port)			-0.44***	-0.47***			0.013
Ln(travel time to 100K city)					-0.36***	-0.34***	-0.48***
Ln(potential production, low inputs)	0.18***	0.18***	0.18***	0.18***	0.18***	0.18***	0.18***
Ln(100 km^2 pop. density)	-0.55***	-1.25***	-1.34***	-1.32***	-0.54***	-1.27***	-1.38***
Ln(100 km^2 pop. density), squared		0.049***	0.056***	0.054***		0.051***	0.059***
Total observations	15,122	15122	15122	15136	15125	15125	15125
Pseudo R-squared	0.125	0.126	0.127	0.127	0.125	0.125	0.127
Territorial fixed effects	Yes	Yes	yes	yes	Yes	yes	yes

Source: Authors' estimates.
Notes: * significant at 10%; ** significant at 5%; *** significant at 1%.

Table B.2.Major road sections upgraded to asphalt for the scenario of governmental road network system upgrade

SECTION	Length (km)	SECTION	Length (km)	SECTION	Length (km)
Aeroport de Ndjili-Nsele	29	Kasomeno-Kasenga	61	Mpa-Nioki	57
Akula-Gemena	115	Kasomeno-Lubumbashi	140	Mukulia-Lebia	34
Bagata-Pinanga	44	Kasongo-Matala	129	Musango-Bulungu	61
Bandundu-Mpoko	102	Kavumu-Minova	90	Mwenga-Burhale	71
Batshamba-Riviere Loange	119	Kenge-Kikwit	310	Ndoluma-Beni	103
Bendela-Bunkulu	13	Kikwit-Batshamba	89	Nguba-Likasi	61
Beni-Kasindi	78	Kinshasa (Cite verte)-Aeroport de Ndjili	27	Niania-Komanda	286
Besefe-Bokatola	22	Kisangani-Opala	3	Nioki-Bendela	80
Bikoro-Besefe	60	Kisangani-Pene Tungu	100	Nsele-Kenge	203
Boma-Matadi	1	Kisangani-Ubundu	117	Pene Tungu-Lubutu	132
Boyabo-Libenge	18	Kisangani-Yangambi	89	Pinanga-Kutu	89
Boyabo-Zongo	91	Komanda-Bunia	69	Pont Lulua-Kananga	12
Boyamba-Mpa	39	Komanda-Erengeti	72	Riviere Loange-Tshikapa	122
Boyamba/Mpa-Selenge	160	Kutu-Inongo	99	RN18 (Kinimi)-Bagata	104
Boyasegbwe-Mobanza	57	Lac Mukamba-Mbuji Mayi	108	Rutshuru-Bunangana	24
Bukavu-Kamanyola	43	Lebama-Tsebedin (RN209)	55	Tshikapa-Bulungu	161
Bukavu-Kavumu	38	Lebia-Mambasa	103	Walikale-Masisi	124
Bulungu-Pont Lulua	60	Likasi-Kambove	5	Weti-Besefe	71
Bumba-Lisala	143	Likasi-Lubumbashi	126		
Bunduki-Bumba	119	Lisala-Akula	2		
Bunia-Mahagi	168	Lubumbashi-Kasumbalesa	90		
Burhale-Bukavu	51	Madula-Niania	312		
Businga-Lisala	190	Maloba-Kasongo	109		
Erengeti-Beni	50	Masisi-Sake	56		
Gemena-Boyabo	154	Matadi-Kinshasa (Cite verte)	329		
Gemena-Karawa	71	Matala-Mwenga	198		
Goma-Ndoluma	227	Mbandaka-Ingende	138		
Inongo-Weti	88	Mbau-Kamango	61		
Kabinda-Maloba	258	Mbuji Mayi-Kabinda	161		
Kalamba-Bikoro	48	Mbuji Mayi-Mwene Ditu	120		
Kamanyola-Uvira	78	Minova-Sake	18		
Kananga-Lac Mukamba	85	Mogalo-Bari	47		
Karawa-Boyasegbwe	14	Mombanza-Businga	13		
Kasenyi-Bunia	42	Mongata-Bandundu	235		

Source: Rdc-humanitaire (2009).

Table B.3. Major road sections upgraded to asphalt for the scenario of the comprehensive plan

SECTION	Length (km)	SECTION	Length (km)	SECTION	Length (km)
Aeroport de Ndjili-Nsele	29	Kasomeno-Lubumbashi	140	Ndu-Bondo	192
Aketi-Bunduki	75	Kasongo-Matala	130	Nguba-Likasi	61
Akula-Gemena	119	Kasumbalesa-Sakania	126	Niania-Komanda	290
Banana-Moanda	7	Kavumu-Minova	90	Nsele-Kenge	203
Baraka-Fizi	35	Kenge-Kikwit	310	Opala-Otala	131
Batshamba-Riviere Loange	119	Kikwit-Batshamba	89	Osekola-Lodja	212
Beni-Kasindi	74	Kilwa-Kasomeno	200	Oso-Walikale	107
Boma-Matadi	234	Kinshasa (Cite verte)-Aeroport de Ndjili	27	Otala-Ikela	49
Boma-matadi	7	Kisangani-Opala	215	Pene Tungu-Lubutu	132
Bondo-Buta	199	Kisangani-Pene Tungu	100	Pont Bukama-Nguba	257
Boyabo-Libenge	18	Komanda-Erengeti	72	Pont Lubilashi-Pont Bukama	389
Bukavu-Kamanyola	43	Lac Mukamba-Mbuji Mayi	108	Pont Lulua-Kananga	12
Bukavu-Kavumu	38	Likasi-Lubumbashi	126	Pweto-Kilwa	132
Bulungu-Pont Lulua	60	Lisala-Akula	171	Riviere Loange-Tshikapa	122
Bumba-Lisala	143	Lodja-Lukibu	200	Sake-Goma	25
Bunduki-Bumba	119	Lubumbashi-Kasumbalesa	90	Tele-Kisangani	222
Burhale-Bukavu	51	Lubutu-Oso	87	Tshikapa-Bulungu	161
Buta-Tele	94	Lukibu-Mashala	60	Uvira-Baraka	83
Dulia-Aketi	48	Madula-Niania	316	Uvira-Makungu	2
Erengeti-Beni	64	Makungu-Kalemie	140	Walikale-Hombo	83
Fizi-Makungu	122	Maloba-Kasongo	109		
Gemena-Boyabo	154	Mashala-Mwamba Mbuyi	119		
Goma-Ndoluma	232	Matadi-Kinshasa (Cite verte)	329		
Hombo-Miti	75	Matala-Mwenga	198		
Ikela-Isunguma	104	Mbuji Mayi-Kabinda	162		
Isunguma-Osekola	16	Mbuji Mayi-Mwene Ditu	120		
Kabinda-Maloba	258	Minova-Sake	18		
Kalemie-Pweto	389	Moanda-Boma	95		
Kamanyola-Uvira	102	Mwene Ditu-Pont Lubilashi	95		
Kananga-Lac Mukamba	85	Mwenga-Burhale	71		
Kananga-Mbuji Mayi	3	Ndoluma-Beni	105		

Source: Rdc-humanitaire (2009).

Table B.4. Crop prices

Crop	Price (US$/kg)	
Beans	488.3	
Cassava	294.5	
Coconuts	101.8	
Coffee	428.4	
Cotton	535.3	
Groundnuts	363.9	
Maize	213.2	
Millet	502.1	
Palm kernels	125.0	
Palm oil	452.8	
Plantains	98.6	
Potatoes	361.2	
Rice	161.5	
Sorghum	313.8	
Soybeans	80.8	
Sugarcane	120.7	
Sweet potatoes	115.7	
Wheat	167.4	
Barley	115.3	(South Africa)

Source: Unless otherwise specified, the prices are either for Congo (DRC) or Cameroon and were collected from http://faostat.fao.org/site/570/DesktopDefault.aspx?PageID=570.

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IFPRI HEADQUARTERS

2033 K Street, NW
Washington, DC 20006-1002 USA
Tel.: +1-202-862-5600
Fax: +1-202-467-4439
Email: ifpri@cgiar.org

IFPRI ADDIS ABABA

P. O. Box 5689
Addis Ababa, Ethiopia
Tel.: +251 11 6463215
Fax: +251 11 6462927
Email: ifpri-addisababa@cgiar.org

IFPRI NEW DELHI

CG Block, NASC Complex, PUSA
New Delhi 110-012 India
Tel.: 91 11 2584-6565
Fax: 91 11 2584-8008 / 2584-6572
Email: ifpri-newdelhi@cgiar.org