POLICY AND ECONOMIC CONSIDERATIONS FOR GLOBAL PUBLIC GOODS PROVISION: AGRICULTURAL AND HEALTH R&D FUNDING FROM THE PRIVATE, PUBLIC, AND PHILANTHROPIC SECTORS

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Abstract

Funders from the private, public, and philanthropic sectors all play a role in investing in global public goods such as R&D, but have different incentives for doing so. In the broadest terms, private investors seek to maximize profit, public funders have political, economic, and humanitarian objectives, and philanthropists seek to maximize a social rate of return. In this paper we develop a framework - from the perspective of a global planner - for considering how different characteristics of agricultural and health R&D affect the relative incentives of alternative funding sources. We then compare private, public, and philanthropic funding against hypotheses for how we might expect a global planner to allocate funding from each source. For agricultural R&D, consistent with expectations we find that private funding focuses on crops with higher market returns; however, contrary to expectations we find that public and philanthropic spending also goes overwhelmingly to these same crops rather than crops not targeted by private funding. For health R&D, consistent with expectations we find that private funders target diseases with higher potential financial returns, while public and philanthropic sources allocate a relatively greater share of their R&D funding for diseases that are incident in low-income countries.

Key words: agricultural R&D, health R&D, finance, global public goods, philanthropy

1   Introduction

When research and development (R&D) produces knowledge that can be used repeatedly (non-rival consumption) and that is costly to exclude from non-payers, that R&D exhibits public good characteristics, and is hence likely to be under-provided by markets relative to the socially optimal level (Samuelson, 1954). Arrow (1962) and Nelson (1971) were among the first to argue not only that the social returns to research investment exceeded the private returns realized by individual firms, but also that scientific and technical knowledge have large and far-reaching marginal social benefits at low marginal cost. When the potential pool of beneficiaries of R&D is geographically diverse, as in the case of investments in agricultural and health R&D for crops and diseases with applications across multiple countries and regions, such R&D may be considered a regional or global public good (GPG) (Mondiale, 2001). GPGs may be especially vulnerable to under-provision in the absence of difficult-to-realize coordination across multiple potential beneficiaries, and across multiple potential funders (Kaul, 2012; Cepparulo & Giuriato, 2016) and given widespread disparities in resources across potential beneficiaries and potential providers (Oerlemans & Meeus, 2001).

From the perspective of a global planner, the problem of public goods provision is one of minimizing the true cost of providing the socially optimal level of a given good. In the case of agricultural and health R&D, investment decisions may take place at the sub-national, national and international levels, and may include private, public, and philanthropic funders. An efficient global planning solution would seek to finance GPGs up to the socially optimal level while preventing duplicative funding and maximizing the contributions of the private sector (i.e., encouraging all private sector contributions with positive net economic returns as we assume they have the most stringent objectives – financial profit from their investment – but weakest locational preferences). But only a small body of literature addresses the relative advantages of alternative funding options for providing GPGs (Mondiale, 2001; Sagasti & Bezanson, 2001; Anand, 2002; Kaul, 2012; Cepparulo & Giuriato, 2016). An even smaller literature examines alternative funding options for GPGs specifically related to agricultural and health R&D (Delisle et al., 2005; Naseem et al., 2010; Spielman, Hartwich & Grebmer, 2010; Buckley et al., 2014). This paper contributes to the literature on efficient provision of public goods by considering variations in the benefits and costs perceived by funders across different sectors from investing in different types of agricultural and health R&D, with an emphasis on R&D relevant to developing countries.

While past work has often focused broadly on the roles of public sector actors in GPG funding, we draw upon more recent work by Cepparulo & Giuriato (2016), Kharas & McArthur (2014), Pratt et al. (2012), and Popa et al. (2011) to establish a set of specific theoretical expectations surrounding the potential roles of private, public, and philanthropic funders for agricultural and health R&D. A priori, theory suggests that profit maximization motives would lead the private sector to invest in R&D for market-oriented crops and pharmaceuticals targeting diseases with higher potential for financial returns, and to focus their private investments on crops/diseases found in geographic contexts where firms are better able to capture those returns. In contrast, public and philanthropic funding sources might fund R&D for a greater variety of crops and

diseases, prioritizing R&D investments with higher potential net marginal social returns. We expand upon these fundamental theoretical assumptions, outlining a framework that specifies the underlying financial and social objectives of different types of public good funders in terms of anticipated benefits, anticipated costs, and risk and time preferences.

Based on this framework, we outline a set of hypotheses for how a global planner might allocate funding from each source to minimize aggregate costs and realize the socially optimal level of provision for different types of agricultural and health R&D. We then test these hypotheses by examining available statistics on funding for agricultural and health R&D from private, public and philanthropic sources. Within agricultural R&D funding we separately consider spending on research from each funding source for "cash crops" such as palm oil, cotton and tobacco that are grown primarily for sale and other market-oriented crops such as fruits and vegetables, "commodity grains" such as maize, rice, or wheat that may be consumed by producers but are also frequently sold in markets, and "orphan crops" including roots and tubers, sorghum, millets, common bean, and cowpea that may be sold but are more commonly grown for own consumption and subsistence, and are scientifically neglected relative to their contribution to food security in poor regions (Naylor et al., 2004). For health R&D, we consider overall spending targeting all diseases and health issues and spending on "neglected diseases," which "disproportionally affect people in developing countries" and for which there is " insufficient commercial market to attract R&D by private industry" (Chapman et al., 2016). By comparing trends in funding from private, public and philanthropic sources against hypotheses for how a global planner might allocate funding from each source, we seek to inform ongoing debates around who should fund agricultural and health R&D, given limited global resources for investment.

The outline of this paper is as follows. Section 2 models the drivers of funder's decisions to invest in R&D public goods, then summarizes the public goods characteristics of different sub-categories of agricultural and health R&D. Based on these characteristics, we present hypotheses for how the public and philanthropic sectors would be expected to fund different R&D types from the perspective of an efficiency-oriented global planner. Section 3 summarizes different funders' total and relative contributions to agricultural and health R&D over time, including both overall spending and spending targeting different categories of crops and diseases. In section 4 we compare the evidence of funding allocation by sector to R&D categories as an initial assessment of whether the hypotheses appear to hold. Section 5 discusses the findings and limitations of the analysis.

2   Funders' incentives and capabilities for providing global public goods

Stiglitz (1999) argues that most knowledge can be classified as a global public good, reasoning that a universal scientific theory derived from research in a single country is no less true elsewhere in the world. R&D is one way of generating knowledge, and it exhibits many global public good characteristics. However, R&D and the outcomes it produces are not necessarily "pure" public goods (exhibiting both low rival consumption and high costs of excluding non-payers), insofar as there may be mechanisms, such as intellectual property protections, for

restricting people from accessing their benefits (thus attracting private investment). R&D public goods are also only "global" insofar as their benefits may extend beyond some – if not all – international borders. Public goods from R&D targeting specific crop or disease strains may be more or less global in extent, depending on characteristics of the crop or disease, and depending on the surrounding legal and institutional context.

Nonetheless, the literature bears out the notion that the results of the R&D process produce real social benefits. Several studies offer estimates of the social benefits from agricultural R&D funding, which include decreased hunger and improved food security (El-Sharkawy, 2006; Echeverria & Beintema, 2009; Piesse & Thirtle, 2010), greater environmental sustainability and preservation of natural resources (El-Sharkawy, 2006; Echeverria & Beintema, 2009), and reductions in poverty (Alene & Coulibaly, 2008; Piesse & Thirtle, 2010). Alston et al.'s (2000) meta-analysis finds an average social rate of return to agricultural R&D (across 292 publications) of 99.6% for all countries, suggesting that on average $100 of agricultural R&D invested yielded $199.60 in social benefits, beyond the private return on investment. More recent estimates of returns to African food and agricultural R&D from 113 studies published from 1975-2014 find an average benefit-cost ratio of 30.1 (Pardey et al., 2016a). Similarly, health R&D contributing to new drugs or vaccines, for example, may improve health and educational outcomes (Røttingen et al., 2013). Kremer's method estimates that the social value of a pharmaceutical is generally 2.5 times the private value (Lybecker & Freeman, 2007). This finding is consistent with Sussex et al.'s (2016) study that estimates UK public investment in biomedical and health research generates a 17% social return on investment.

The products (i.e., new knowledge, technologies, improved crop varieties, vaccines) of R&D for agriculture and for health can confer almost completely non-rivalrous benefits to the global public, and are therefore considered "best shot" public goods, where the largest effort determines the public good level (Sandler, 2003). For example, if one country or organization invests in R&D for a new crop variety, the knowledge can spread to other countries without requiring separate investments to achieve the same knowledge (to the extent that the variety is appropriate for cultivation in different locations or the disease is incident). Jayaraman & Kanbur (1999) find under some game theoretic assumptions that "best-shot" public goods should be directly provided by donors with no accompanying income transfers (e.g., foreign aid) to recipients as the marginal benefits and incentive for additional provision are zero (assuming donors have greater resources). And though a single organization can develop a new treatment or technology through basic health R&D in isolation (Arce & Sandler, 2002), global cooperation may still be helpful to identify the optimal provider and potentially share the costs (Anand, 2002).

2.1 Drivers of agricultural and health R&D investment by sector

Potential funding sources to provide R&D public goods include:

- Private funders, i.e. *for-profit firms* (Pratt et al., 2011; Mondiale, 2001);
- Public funders, i.e. *high-income country governments* (Matthews & Shulman, 2005; Reisen, Soto & Weithöner , 2008), *low-income country governments* (Sagasti & Bezanson,

2001)*, and *international multilateral organizations* (including multilateral aid
organizations and international partnerships like the CGIAR (Ferroni, 2002));

- Philanthropic funders, i.e. *foundations* (Anand, 2002; Main, 2013); and
- *Partnerships*, usually between a public or philanthropic source and one or more private sources in order to leverage the strengths of each funder (Brown, 2008; Spielman, Hartwich & Grebmer, 2010).

With identical investment objectives, allocative efficiency would have a global social planner direct each funder to invest up to the point where the marginal net returns per unit of investment are equal. The solution for goods with public good characteristics, however, is complicated to the degree that the good generates biophysically non-excludable benefits (which may be more or less excludable via legal means and more or less local or global in extent), non-rivalrous benefits that once produced can be consumed by others at a zero to low incremental cost, and that the objectives of funders differ.

For any given public good investment decision, depending on the funder, return on investment calculations can be financial or social in nature. Equation 1 provides a simple model of the factors that investors may consider in determining whether to invest in providing a public good, in this case, R&D. The 'expected' portion in calculations of the net present value (NPV) of R&D investment is a holistic accounting of the technical (or scientific), economic, and regulatory uncertainties of moving an R&D product through each phase to market. The probability to market is the overall probability of success – the product of the conditional probabilities of successfully getting through each phase in the R&D process. The first set of costs is incurred with certainty (spent whether successful or not) while subsequent costs are only incurred if successful in the previous phase.

$$Eqn.\,1{:}\,E(NPV) = \left[prob.\,to\,market\left(\frac{R\,+\,SOC\,(0\,\leq s \leq 1)}{(1+r)^t}+\right)*(0\,\leq loc_R\,weight \leq 1)\right]$$
$$-\sum_i\left[prob.\,(phase_i\,|\,phase_{i-1})\left(\frac{C_i}{(1\,+\,r)^{t_i}}\right)*(0\,\leq loc_C\,weight \leq 1)\right]$$

Financial returns to R&D investment (*R*) and any social returns (*SOC*) are primarily realized once the products developed as a result of the research reach the market (though knowledge is generated and patents may be purchased at earlier stages). Financial returns reflect monetized gains to funder of R&D, while social returns are experienced by society more broadly but may still be valued by the funder. The relative importance to investors of achieving social returns is captured by the parameter *s*. Costs (*C*) are incurred at each phase of research. These phases of R&D vary by sector (e.g. agriculture and health), and these differences can be incorporated into this framework. Preferences for where the returns and expenditures from R&D investments are concentrated are captured through cost and returns location weights (*loc weight*). A discounting term (*r*) reflects time preferences of funders: the more numerous and risky the phases of research, or the greater the time lag between expenditures and returns (*t*), the greater the discounting. Present value accounts for the often very long time lag between cost expenditures

and market returns via discounting those returns by the real opportunity cost of capital over time (Echeverria & Beintema, 2009).

Financial returns (*R*) are a function of market size, market share, consumer willingness-to-pay, and excludability. Size refers to the number of potential transactions, which derives from the number of consumers and the transactions per consumer – a distinction to reflect a difference between a one-shot vaccine compared to a chronic drug treatment, or the rate at which a hybrid seed's vigor declines. Consumer willingness to pay is primarily a function of ability to pay (i.e., income) and the price of complementary and substitute goods – the latter of which also reflects market share and any seller's ability to charge a price above marginal cost.

Returns also depend on the degree to which the public good is physically "excludable" (e.g., whether a drug offers lifelong protection or must be re-administered, or whether a crop variety is open-pollinated or must be re-purchased each year) or legally protected (e.g., via patents). For expository purposes we distinguish between biophysical and legal excludability. Biophysical excludability is low for knowledge, such as a discovery of a genetic code that can be shared at low cost with other researchers, or the economic benefits to smallholder farmers from the free exchange of improved open-pollinated variety seeds, or the health benefits to households arising from herd immunity following the introduction of a vaccine. But holding constant the biophysical characteristics of the product, excludability rises with legal property rights protection, and the degree to which *de facto* property rights approach *de jure* property rights.

Costs are presumed to vary by the phase of R&D, and include fixed costs, such as lab equipment and space, variable costs in the form of researchers and materials, and regulatory compliance costs. The cost of product development and time to market are a function of the stage of science, the complexity of the pathogen or genetic code, and regulatory requirements and processes (Rawlins, 2004). Investors may be able to reduce R&D costs by paying for the rights to initial research outputs for which the time to market for applied products is reduced. The initial start-up research costs as well as ongoing development costs of maintenance or updating can be substantial (Barrett, 2003). Countries' regulatory structures may also impose costs for R&D provision.

We assume that private for-profit sector investors are interested in maximizing the expected present value of profit across their investment options, which depends on their ability to capture financial returns (*R*) from their R&D investments (Stiglitz, 1999). We assume that the public and philanthropic sectors do not disdain financial returns, but are relatively more interested in potential social returns (*SOC*), such as the non-market value of reducing hunger or the Disability-Adjusted Life Years (DALYs[2]) due to particular diseases through improved crop varieties or new vaccines, respectively. Mondiale (2001) suggests that while private companies measure returns in terms of profits, philanthropic foundations seek the maximum marginal social

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[2] DALYs attempt to measure the overall burden from a disease by combining life years lost and a weighted measure of years disabled by a disease globally in a given year (Arnesen & Nord, 1999), and may reflect part of the potential social benefit from reducing or eliminating a particular disease.

impact of an investment. Provision of R&D public goods is also characterized by high levels of risks, as scientific, market, and regulatory uncertainty may affect the likelihood of achieving returns from R&D investment. Private investors may be willing to accept higher levels of uncertainty if the potential net returns are significant. The public sector may be less willing to tolerate high risk as a result of accountability to their taxpayers. Mondiale (2001) argues that philanthropic organizations are the best funders for such high-risk public goods because "their advantage arises from their mandate and demonstrated willingness to invest early in unproven technologies with potentially widespread benefits" (p. 10).

The public sector is assumed to consider social, economic, political, and humanitarian objectives. Private funders are not expected to have any preferences for the location of R&D benefits or expenditures, while philanthropic and multilateral public funders may prefer the benefits to be concentrated in particular target geographies (Alesina & Dollar, 2000; Lundsgaarde, Breunig & Prakash, 2010; Fitchett, Head & Atun, 2014; The Foundation Center, 2014), or including among low-income populations (Büthe, Major & Souza, 2012). Government public funders may discount benefits that do not accrue to their domestic constituents (as governments are accountable to their taxpayers). Similarly, governments may prefer to concentrate expenditures locally and discount domestic costs, to reflect potential upstream spillovers from local funding. This preference is reflected in the *loc weight* terms in Equation 1, which apply to non-domestic returns (*loc_R weight*) and to domestic costs (*loc_C weight*).

If benefits are excludable, we can expect the same level of provision of a non-rivalrous good from the private or public sector, all else equal. Thus, it is imperfect or costly excludability, and/or marginal social benefits uncaptured through market exchange, that matter for R&D investment decisions. Non-market returns are unlikely to be considered in the benefits calculus of private investors, hence we expect a gap between private and socially optimal provision. In extreme cases where no one can be excluded from the benefits of a global public good such as basic R&D with limited application to end-products, there are limited incentives for any private sector provision (WHO, 2016a). Additionally, poorly remunerative markets relative to high risks of failure and high fixed costs may preclude some private investment. Thus, R&D investments where returns absent social considerations may not be positive likely require philanthropic and public funders.

Table 1. Preferences for R&D Investment by Sector

Preferences	Private	Philanthropic	Public
Financial Returns	Necessary	Not necessary	Not necessary
Social Returns	Not accounted for ($s = 0$)	Necessary (s closer to 1)	Valued to some degree ($s > 0$)
Tolerance for Risk	High if potential net returns are high	High for areas with high social returns	Relatively lower
Location of Returns	Indifferent (loc_R $weight = 1$)	Preferences but ranked below social returns (loc_R $weight = 1$ for areas with high social returns)	Prefer domestic returns (loc_R $weight < 1$ for non-domestic beneficiaries)

Location of Expenditures	Indifferent (loc_C weight = 1)	Indifferent (loc_C weight = 1)	Prefer domestic expenditures (loc_C weight < 1 for domestic expenditures)

Given the differing return on investment calculations adopted by private, public, and philanthropic funders, from an efficient global planning perspective any economically profitable endeavor would be undertaken by the private sector first, and the public and philanthropic sectors would fill in the remaining gap. The reason for this "two-stage" process is both that private investors are expected – all else equal – to have weaker locational preferences (a dollar is a dollar) and that the full opportunity cost of a dollar of private funding is arguably lower, since we assume that non-private investors may seek financial or social returns, but private investors will limit their range of investments to those with positive financial returns. In other words, public and philanthropic funders might behave like the private sector as they can be expected to fund the full range of options (public goods with positive financial returns, or public goods with negative financial returns but positive returns if social impact is considered), but we cannot expect the private sector to fund opportunities that are likely to have a positive net return only if social benefits are considered (in general and as a whole). Hence efficiency requires that the private sector – given current market and regulatory conditions – first fund the subset of investments that meet their more limited objectives.

In reality, there is overlapping funding of some public goods across sectors, and overlap between sectors themselves in the form of partnerships, especially for goods with high initial investments (Sagasti & Bezanson, 2001). Partnerships can improve financial viability for the private sector through tax breaks or loan subsidies that reduce costs, or through direct financial returns (public funding), exclusive rights, and pre-negotiated payment for goods and services that increase economic returns (Brown, 2008). Sandler (1999), however, emphasizes that offering incentives to attract private investment is not costless but rather represents the use of public financial resources.

2.2 Characteristics of agricultural and health R&D public goods

The financial and social returns, costs, uncertainties, and timeline in the above simple model will all be influenced by the particular characteristics of specific agricultural and health R&D investments. For simplicity, we focus in this paper on differences in the potential financial returns, assuming that the most important differential between funders across sectors is the relative size of financial and social returns. We therefore look separately at categories of crops and diseases that differ primarily in terms of the potential financial returns from R&D investments.

Within agricultural R&D funding we separately consider spending on research from each funding source for commodity grains, cash crops and other market-oriented crops, and subsistence crops. Marketability, and consequently financial return on investment, is likely to be greater for R&D targeting widely-traded commodity or cash crops, making such crops a more attractive focus for private R&D investment (McIlroy, 1963). The potential returns from R&D in

subsistence crops primarily consumed by poor households in developing countries are lower, making them less attractive for private funders (Chibnik, 1978).

"Commodity grains" include maize, rice, and wheat, crops that may be consumed by producers but are also frequently sold in markets. "Cash crops" include crops such as palm oil, cotton and tobacco that are grown primarily for sale (Maxwell & Fernando, 1989) and other market-oriented crops such as fruits and vegetables. While maize, rice, and wheat are the most commonly produced crops in many Sub-Saharan African and South Asian countries, other widely-produced crops in these regions receive relatively little research spending. Among crops that are grown primarily for farm household subsistence, we look particularly at "orphan crops" that are scientifically neglected relative to their contribution to food security in poor regions (Naylor et al., 2004). Although there is no definitive list of orphan crops, Varshney et al. (2012) identify twelve orphan crops for which molecular breeding is in the early stages or yet to be started: cassava, sweet potato, coconut, sorghum, yam, groundnut, millets, common bean, chickpea, cowpea, cacao, and pigeonpea. Any of these crops may be sold but they are more commonly grown for own consumption and subsistence, and are also most commonly grown by low-income populations, meaning the potential financial returns from R&D investments in these crops are limited.

In health, the basic science of health R&D tends to not be patentable, from an academic tradition of knowledge exchange and free flow of ideas, and therefore not profitable in and of itself (Congressional Budget Office, 2006). This basic R&D may, however, contribute to vaccines, drugs, diagnostics or other product development with significant financial returns. From 2010-16, private returns of pharmaceutical R&D ranged from 3.7-10.1% (Deloitte, 2017).

For health R&D, we consider overall spending targeting all diseases and health issues and spending on "neglected diseases," defined in the Policy Cures G-Finder reports as diseases that "disproportionally affect people in developing countries," which have a "…need for new products," and for which a market failure exists, "i.e., there is insufficient commercial market to attract R&D by private industry" (Chapman et al., 2016).[4] Although neglected diseases primarily only affect populations in low-income countries while other diseases have more global burdens, the social returns of R&D for neglected diseases have the potential to be very high (Mathers et

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[4] This definition is distinct from "neglected tropical diseases" as defined by the World Health Organization (WHO) (2017): "Neglected tropical diseases (NTDs) are a diverse group of communicable diseases that prevail in tropical and subtropical conditions in 149 countries and affect more than one billion people, costing developing economies billions of dollars every year. They mainly affect populations living in poverty, without adequate sanitation and in close contact with infectious vectors and domestic animals and livestock." There is some overlap among these NTDs and the neglected diseases defined by G-Finder, but we adopt the G-Finder definition of neglected diseases in this paper due to the regular availability of data on R&D spending for these diseases. The WHO also has a typology that sorts diseases into one of three categories (Types I, II, and III) according to the geographic distribution of their relative rates of incidence. In this typology, Type I diseases have a similar disease burden in both developed and developing countries and Types II and III have greater and significantly greater disease burdens in developing countries, respectively (WHO, 2012a). G-Finder defines neglected diseases by more than just geography incidence, but they generally fall into Type II and III of the WHO classification.

al., 2007). The low ability to pay of most of the populations affected by these diseases, however, limits the potential financial returns to R&D investments targeting neglected diseases.

Non-communicable diseases (e.g., cancers, heart disease, etc.), accounted for 1,473 million DALYs in 2015, nearly double the 741 million DALY caused by communicable, maternal, neonatal, nutritional diseases (healthdata.org, 2017). The 2016 G-Finder report estimates total DALYs from neglected diseases at 344.6 million (Chapman et al., 2016), or 15.6% of total global DALYs caused by diseases. Kassebaum et al. (2016) report on the top 15 global causes of DALYs among 315 diseases and injuries. The top cause of DALYs is heart disease (164 million DALYs), followed by cerebrovascular disease (118 million DALYs), and lower respiratory infection (103 million DALYs). The list includes three neglected diseases: diarrheal diseases (#6, 71.6 million DALYs), HIV/AIDS (#10, 66.7 million DALYs), and malaria (#14, 55.8 million DALYs).

3   Methods and Data

Given the nature of the relationship between public goods, potential funding sectors, and the expected costs and benefits of R&D investment, we identify two hypotheses about efficient allocations of R&D funding.

Hypothesis 1 – The public and philanthropic sectors direct a greater proportion of their agricultural R&D funding toward subsistence and "orphan" crops compared to the private sector. Within agricultural R&D, we would expect the private sector to direct more investment toward crops with greater potential financial returns from established markets and potentially higher willingness to pay, namely commodity grains, cash crops, and other market-oriented crops. A recent increase in private R&D investments may be related to the private sector's increased ability to capture financial returns through strengthened plant breeder's rights and patent protections for new plant varieties (Fuglie et al., 2012). We would then expect the public and philanthropic sectors to fill the void created by the absence of private sector funding and focus on R&D for subsistence and "orphan" crops to the extent that such investments offer larger marginal social, rather than financial, returns. As both subsistence and "orphan" crops are important for food security in developing countries and generate significant social returns, (El-Sharkawy, 2006; Echeverria & Beintema, 2009; Piesse & Thirtle, 2010), public and philanthropic sources likely have an interest in providing R&D funding to these categories of crops, which the private sector is unlikely to fund.

Hypothesis 2 – The public and philanthropic sectors direct a greater proportion of their health R&D funding toward neglected diseases compared to the private sector. The potential financial returns for diseases that are also incident in high-income countries is generally greater than for neglected diseases. Thus we would expect private R&D funding to concentrate on diseases that are incident among higher-income populations and higher willingness (or ability) to pay, leaving the public and philanthropic sectors to fill gaps in funding for neglected diseases.

We test each of these hypotheses by collecting and analyzing publicly available data on spending from each sector for agricultural and health R&D overall and for specific categories of crops and diseases. We first report available estimates on the distribution of R&D funding by sector, and then compare levels of funding by sector to our hypotheses outlining the expectations for how an efficient global planner would allocate public and philanthropic R&D funding. We then further explore potential correlates of public and philanthropic R&D investment by considering whether agricultural R&D funding levels are associated with crop production or export value and whether health R&D funding levels are associated with the burden of disease for different diseases, as measures in Disability-Adjusted Life Years (DALYs).

For private agricultural R&D spending, we draw on estimates from the United States Department of Agriculture (USDA) Economic Research Service and from the literature. Several sources discuss the geographic location of the firms investing in agricultural R&D, and a few also report on which crops receive most private sector R&D investment. For public agricultural R&D spending, we draw on data from the CGIAR's Agricultural Science and Technology Indicators (ASTI) database. The ASTI reports on global public agricultural R&D spending by country and region, as well as on the number of full-time equivalent (FTE) public sector agricultural researchers. The information on researchers is further broken out by the crops with the researchers focus on, supporting analysis of what crop categories receive more public R&D investment. For philanthropic spending for agricultural R&D we rely on estimates from the literature. Publicly available data on philanthropic R&D spending are limited. We draw data on crop production and export values from the Food and Agriculture Organization of the United Nations (FAO)'s FAOSTAT database.

For health R&D spending, we rely on data from four main sources in the literature. Røttingen et al. (2013) provide 2009 data on total health R&D spending, as well as neglected disease R&D spending by sector. One limitation is that the authors were unable to disaggregate health R&D by sector for all global health R&D spending. Disaggregation was possible, however, for a "subset of mainly high-income countries" which together contributed 90% of all health R&D. Jamison et al. (2013) provide data on health R&D funding by sector and to selected categories of diseases. Chakma et al. (2014) report total health R&D funding by sector over the period of 2007 to 2012, and do not report separately on neglected disease R&F funding. One limitation is that the data capture spending from the US, Canada, Europe, and the Asia-Oceania region, so funding originating outside those geographies (e.g., South America and Africa) is excluded. Viergever & Hendricks, (2016) provide estimates of philanthropic health R&D funding, collecting totals for the largest philanthropic funders. In addition to these sources, we also draw upon data from the G-Finder report, an annual survey in which 185 public, private, and philanthropic organizations complete a survey on their funding levels for neglected disease R&D. The most current funding estimates come from the 2016 G-Finder (Chapman et al., 2016), and we use other G-Finder reports to capture funding estimates in a given year for the purposes of comparing between studies. The G-Finder report also includes DALY estimates for each disease category, which were drawn from the Global Burden of Disease Study 2015 (GBD, 2015).

4   Private, public, and philanthropic funding for agricultural and health R&D

As of 2008, combined public and private agricultural R&D spending amounted to $40.1 billion[5], with $31.7 billion of this total (79%) comprised of public spending (Beintema et al., 2012). More recent figures compiled by the International Science and Technology Practice and Policy Center suggest total public and private agricultural *and* food R&D spending in 2011 was $69.3 billion[6], with $38.1 billion of this total (55.1%) comprised of public spending (Pardey et al., 2016b). The amount of global spending on agricultural R&D has increased in both the public and private sectors over the past decade – the USDA Economic Research Service (2014) reported that total worldwide private agricultural R&D expenditures increased from $5.6 billion[7] in 1994 to over $11 billion in 2010, at an average annual growth rate of 3.6%. Limited evidence is available for philanthropic investments in agricultural R&D. Large philanthropic organizations, such as the Ford Foundation and Rockefeller Foundation, have played significant roles in funding agricultural innovation (Stansfield et al., 2002), but the total financial contribution of charitable foundations is unknown.

The majority of private sector agricultural R&D was conducted by firms in developed countries (Fuglie et al., 2011), and over half of public R&D spending comes from high-income countries, though the role of China and India in funding agricultural R&D is growing rapidly (Beintema et al., 2012).

In the health sector, the amount of total global spending (private and public) on health R&D has increased dramatically since the 1980s. In 1986, there was an estimated $30 billion invested globally in health R&D; in 2005, the estimate was $160 billion and in 2010, the estimate reached $240 billion[8] (Røttingen et al., 2013). Of the $240 billion spent, 89.5% ($214 billion) came from public, private, and philanthropic sources in high-income countries, only .1% ($200 million) came from those sectors in low-income countries, and the remaining 10.4% from upper-middle and lower-middle income countries (Røttingen et al., 2013).

Røttingen et al. (2013) report that investment is skewed across disease types, finding that "Proportions of ongoing clinical trials addressing type II and III diseases are low; and the geographical distributions of health R&D investments, clinical trial research, and health research publications are heavily skewed towards high-income countries". Jamison et al. (2013) reinforce the same point, concluding that "…only about $3 billion[9] is spent annually on R&D for infectious diseases of particular concern to low-income and middle-income countries, representing just 1–2% of total 2009 R&D spending"[10].

Chakma et al. (2014) report that biomedical R&D expenditures by the public sector and private industry in the United States, Canada, Europe, and in Asia-Oceania amounted to $268.4 billion in 2012. Aggregate global health R&D spending in these regions has been relatively steady since 2007, but the U.S. expenditures and share of global spending decreased over this time period—

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[5] All estimates from the 2012 ASTI report are in 2005 purchasing power parity (PPP) adjusted dollars
[6] 2009 PPP dollars
[7] 2010 U.S. Dollars
[8] All estimates in Røttingen et al., 2013 are in 2010 purchasing power parity (PPP) adjusted dollars
[9] 2011 dollars
[10] Jamison et al. refer here to the G-Finder definition of neglected diseases.

largely due to decreased private investment. This gap has been replaced by growth in public and private spending in the Asia-Oceania region (Chakma et al., 2014). Røttingen et al. (2013) find that in 1986, 2005, and 2010, the amount of health R&D across all sectors directed at health problems in low- and middle-income countries increased from $1.6 billion to $5 billion to $26 billion, respectively.
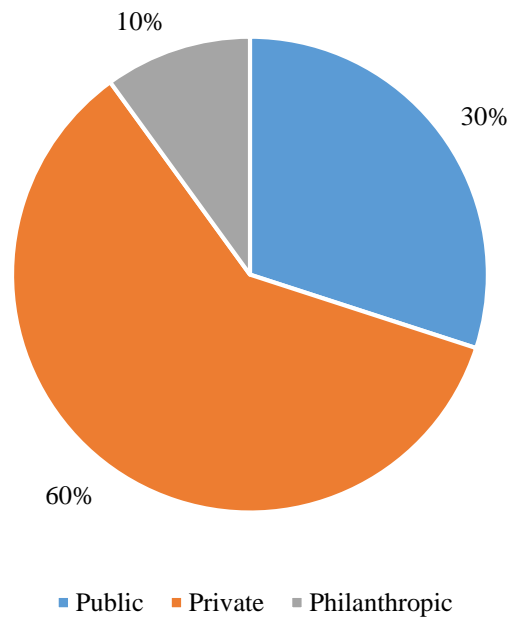
Figure 1. Proportion of Agricultural R&D Funding by Sector, 2008
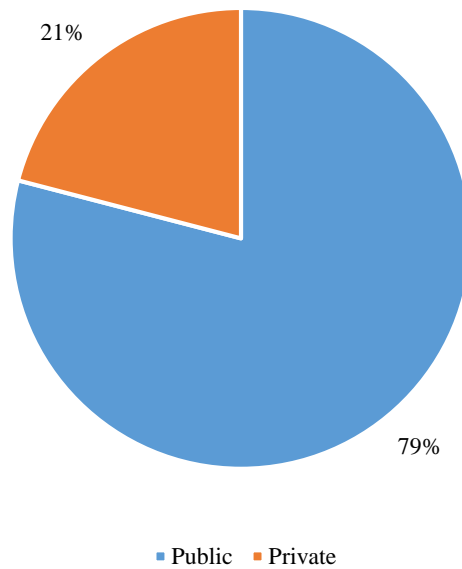
Source: Beintema et al. (2012)

Figure 2. Proportion of Health R&D Funding by Sector, 2009

Source: Røttingen et al., 2013; breakdown of funding from subset of mostly high-income countries representing about 90% of total health R&D funding globally

4.1 Private investment in agricultural R&D

According to Fuglie et al. (2016), total worldwide private agricultural R&D spending was $12.9 billion in 2014.[11] This represents a doubling of total spending from $6.4 billion in 1990, with an average annual growth rate of 3% during 1990-2003 and over 7% during 2003-2014. The vast majority of the increase in spending since 1994 stems from increased funding for crop improvement (USDA Economic Research Service, 2014). Of the $12.9 billion spent on agricultural R&D in 2014, approximately 59% was spent on crop R&D, 17% on animal R&D, and 24% on farm machinery R&D (Fuglie et al., 2016).

In 2010, 95% of private sector agricultural R&D was conducted by firms in developed countries, but a significant number of these companies had research bases in developing countries in order to access these markets (Fuglie et al., 2011). Beintema et al. (2012) report that large middle-income countries, in particular India and China, are also driving growth in private agricultural R&D spending, while most small developing countries, particularly in Sub-Saharan Africa, report stagnant spending growth in private agricultural R&D (IFPRI, 2012).

Fuglie et al.'s (2011) study identified several hundred companies participating in formal agricultural R&D, but each agricultural R&D sub-sector (e.g., seeds/biotechnology, pesticides, and fertilizers, etc.) was dominated by the ten largest firms, which together accounted for at least 80% of total R&D. Fuglie et al. (2016) find four firms spent over $1 billion on agricultural R&D in 2014: Bayer (Germany), Dupont (USA), Monsanto (USA), and Syngenta (Switzerland).

Pal, Rahija, & Beintema, (2012) find that private funding for agricultural R&D accounted for almost 20% of total agricultural R&D spending in 2008. ASTI data analyzed by Beintema et al. (2012) support this finding. Estimates of private spending on agricultural R&D in developing countries as a percentage of total global spending on agricultural R&D between 2000 and 2010 range from between 6% (Naseem et al., 2010) to 7% (Beintema & Stads, 2008). Pardey et al. (2016c) find that for each private sector agricultural R&D dollar spent in high-income countries, low-income countries spent only 0.8 cents.

Overall, less commonly-traded crops or subsistence crops like cassava, pearl millet, and sorghum are characterized by substantially lower levels of private research intensity than more market-oriented crops like maize, vegetables, and palm oil (Naseem et al., 2001; CGIAR, 2011). Low levels of private research are also observed for smallholder cash crops like groundnuts in Central and West Africa (Johnson et al., 2011). Fuglie's (2016) analysis of private sector R&D spending finds that "orphan crops", notably root and tuber crops such as potato, cassava, and sweet potato, as well as small-holder tree crops such as coffee and cacao receive very little investment.

Padulosi et al. (2002) report an emphasis of spending on hybrid crops, for which the loss of effectiveness in subsequent generations requires farmers to repurchase new seed. Figure 3 shows Fuglie et al.'s (2016) estimates of private crop R&D by commodity. Private crop R&D spending focuses on large-acre market-oriented crops, in particular corn, soybeans, and wheat, in addition to small-acre cash crops like fruit and vegetables. In comparison, commodities widely consumed
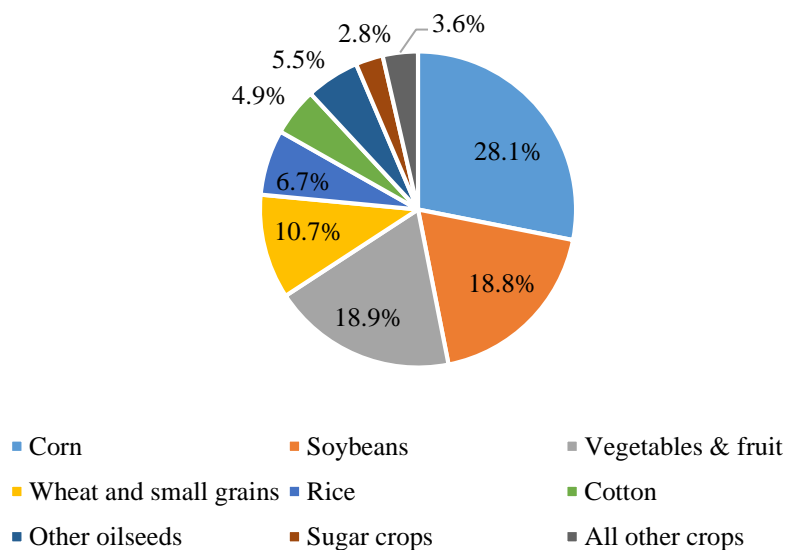
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[11] 2005 PPP Dollars

in low-income countries such as root and tuber crops, bananas and plantains, certain types of vegetables and fruit crops, and small-holder tree crops such as coffee and cacao receive relatively low levels of private spending. The authors also find that private R&D spending relative to the gross production value of the commodity is highest for market-oriented crops. Private R&D spending amounts to 2.3%, 1.8%, and 1.6% of the production value of soybeans, corn, and other oilseeds, respectively.

Figure 3. Private Crop R&D Spending by Commodity, 2014

■ Corn	■ Soybeans	■ Vegetables & fruit
■ Wheat and small grains	■ Rice	■ Cotton
■ Other oilseeds	■ Sugar crops	■ All other crops

Source: Fuglie et al. (2016)

In Asia, available published estimates of research funding similarly indicate that private R&D is concentrated in market-oriented crops, such as palm oil, rubber, tea, vegetables, and horticulture, hybrid varieties of rice, sorghum, millet, and maize, and improved livestock (Morris, 1998; Morris, Singh, & Pal, 1998; Pray & Fuglie, 2001; Gerpacio, 2003; Naseem et al., 2010). Morris (2002) finds that in Latin America and Asia, private investment in R&D for maize, a commonly produced and traded crop in these regions, is approximately twice that of the public sector. Gerpacio (2003) reports that the private sector captured nearly 90% of the Asian maize seed market in the late 1990s and early 2000s, and that, excluding India and China, only 75 of 216 maize seed organizations were public in 2003. In Malaysia, seven private companies spent $14.7 million on R&D in 1995, nearly all of which was for oil palm (81%), generally grown as a cash crop (Pray & Fuglie, 2001).

4.2 Private investment in health R&D

Unlike in agriculture, the private sector is the primary source of funding for health R&D, with sources from the United States, Europe, Canada, and Asia-Oceania providing 62.9% of health R&D spending in 2012 ($168.7 billion) (Chakma et al., 2014). Jamison et al. (2013) report that

global spending on health R&D in 2009 by the private sector amounted to $148.8 billion[12] (about 60% of total funding), with the majority of that targeting non-communicable diseases.

The 2016 G-Finder report finds that overall spending on neglected diseases in 2015 was $3.041 billion, with the private sector funding 15% of that total ($471 million) (Chapman et al., 2016). Of this amount, multinational pharmaceuticals contributed 82% ($388 million) and small pharmaceutical and biotech firms contributes 18% ($83 million) (*ibid.*). In contrast, the Bill & Melinda Gates Foundation alone provided $518 million towards neglected disease R&D in 2015 (*ibid.*). The private sector does provide in-kind contributions for neglected disease R&D, including transfer of technology, provision of expertise, teaching and training, and regulatory assistance, but the value of these contributions is difficult to quantify (*ibid.*). In 2015, 72% of private multinational pharmaceutical investment by in R&D for neglected diseases went towards the "big three" infectious diseases: HIV/AIDS, malaria, and tuberculosis (*ibid.*). In contrast, small pharmaceutical and biotech firms contributed only 24.9% of their spending to the "big three."

4.3 Public sector investment in agricultural R&D

The most recent data on public funding for agricultural R&D compiled by Beintema et al. (2012) in the Agricultural Science and Technology Indicators (ASTI) Global Assessment of Agricultural R&D Spending report find that global public spending on agricultural R&D amounted to $31.7 billion in 2008, comprising approximately 79% of total global spending, excluding philanthropic spending. Approximately half of this funding (51%) came from high-income countries and the rest from low- and middle-income countries. Most recent growth in spending can be attributed to middle-income countries (4.4% growth per year) and low-income countries (2.1%) (Beintema et al., 2012), though low-income country spending is still very low relative to middle- and high-income country spending (Figure 4). India and China in particular accounted for nearly half of the global increase from 2000 to 2008, with China increasing public agricultural research spending by 38% and India by 11% during this period (*ibid.*).

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[12] 2011 dollars

Figure 4. Percentage of Public Agricultural R&D Spending by Low-, Middle-, and High-Income Countries, Selected Years
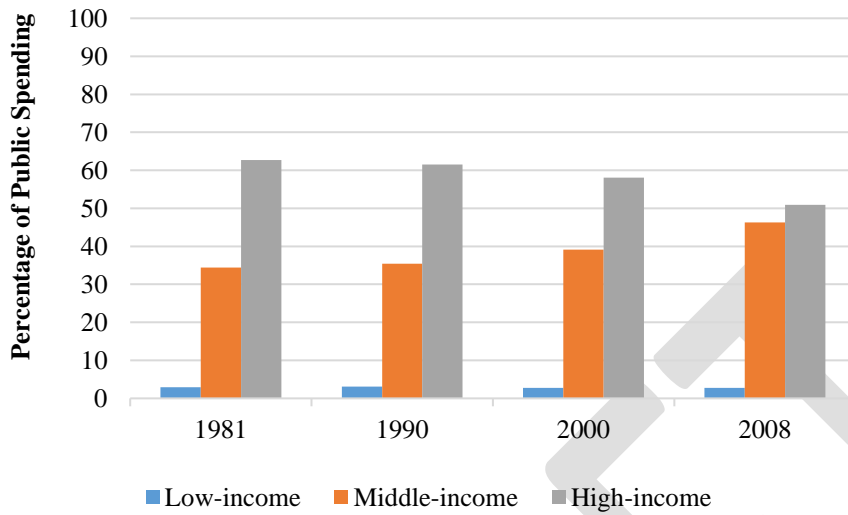
Source: Beintema et al. (2012)

As illustrated in Figure 5, growth in spending in Sub-Saharan Africa and South Asia has been limited. Pardey et al. (2016b) find that in 1980, high-income countries spent $13.25 per person on public food and agricultural R&D compared to $1.73 per person in low-income countries. In 2011, public high-income country per capita spending increased to $17.73 whereas it decreased to $1.51 in low-income countries.

Figure 5. Total Public Agricultural R&D Spending by Low- and Middle-Income Country/Region, 2000-2012
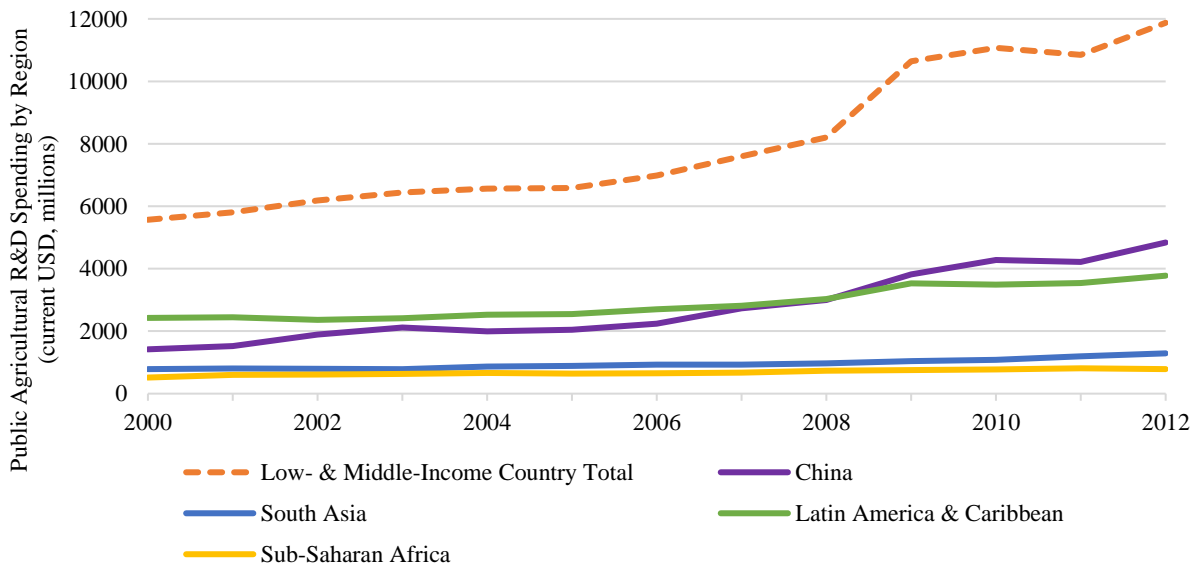
Source: ASTI Database (2017)

U.S. public research spending on specialty crops, of which "orphan: crops are a subset, as a share of total crop spending has been stagnant in the past 25 years despite significant increases in production value of specialty crops (Alston & Pardey, 2008). ASTI data from 2011 further indicate that more commonly-sold crops receive more R&D funding from the public sector than subsistence crops (CGIAR, 2011).

One way to measure public sector funding is to identify the number of researchers paid by the government. Figure 4 summarizes the number of government and higher education researchers across crop categories in Sub-Saharan Africa and South and Southeast Asia.[13,14] Major commodity crop categories – including major cereals but also fruits and vegetables – have the greatest numbers of public researchers, indicating higher levels of government agricultural R&D spending in these areas. We also observe large numbers of public researchers for cash crops cotton and oil-bearing crops. However, nearly 1,000 public researchers, primarily in Sub-Saharan Africa, study "other roots and tubers" including cassava, sweet potato, and yams ("orphan crops", and more typically subsistence crops). Over 1,000 public researchers, primarily in South and Southeast Asia, study other pulses (beans other than soybeans), another key group of subsistence crops. Further, all categories of orphan crops (with the exception of coconut palm) are allocated more researchers than cash crops oil palm and tobacco. Consequently, "orphan" crops do not appear to be particularly neglected by researchers in Sub-Saharan Africa and South and Southeast Asia, though these regions only account for a small amount of global public agricultural R&D funding.

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[13] Non-profit researchers are excluded from this total as they are negligible (less than 4.2 researchers for each crop)

[14] ASTI data for Sub-Saharan Africa includes the following countries: Benin, Botswana, Burundi, Cabo Verde, Central African Rep., Chad, Congo, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Nigeria, Rwanda, Senegal, Sierra Leone, Sudan, Swaziland, Tanzania, Togo, Uganda, and Zimbabwe. ASTI data for South and South-East Asia includes the following countries: Bangladesh, Cambodia, Laos, Malaysia, Nepal, Pakistan, Sri Lanka, and Vietnam.

Figure 6. Public R&D Researchers by Sector in Sub-Saharan Africa and South Asia: Select Crops[15,16], 2014
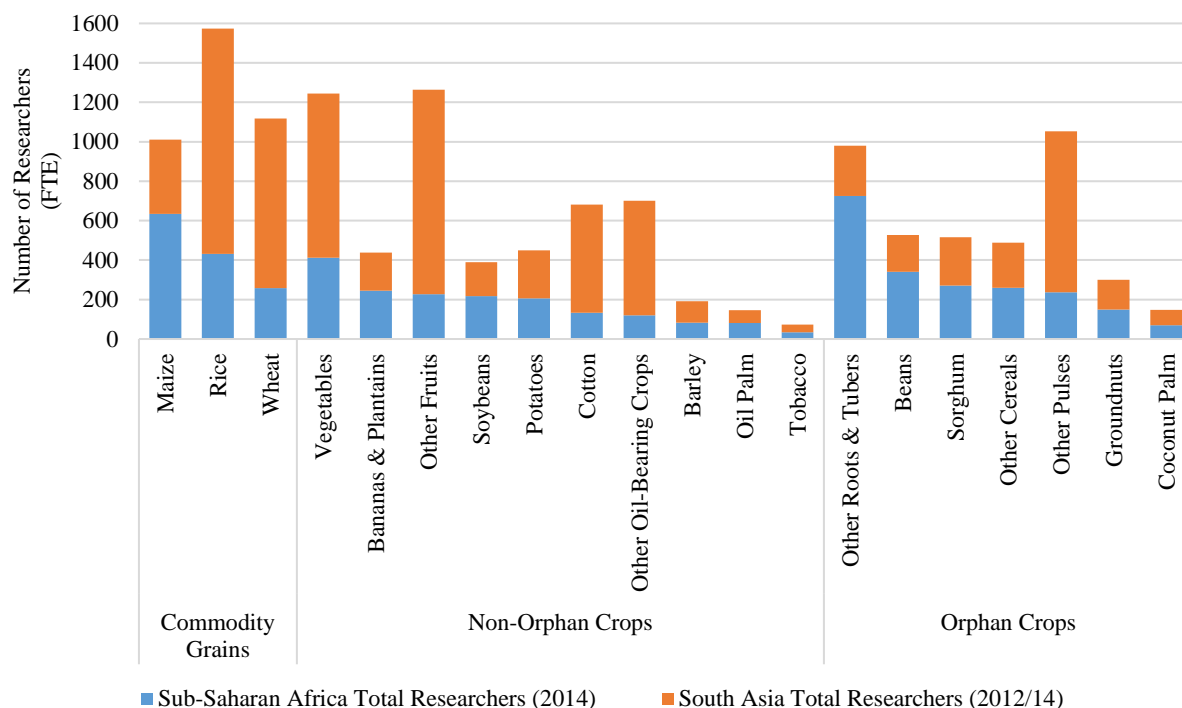
Source: ASTI Database, 2017

4.4 Public sector investment in health R&D

Chakma et al. (2014) identified a 2005 study by the Global Forum for Health Research as the last study that reported global biomedical R&D funding estimates ($160.3 billion in 2005), and indicate that policymakers have since relied on historical trends in the US and forecasting by extrapolating from gross expenditures on science and technology R&D. As such, there appear to be few new studies that empirically assess public sector funding levels of health R&D. Chakma et al. (2014) attempt to fill this gap by providing biomedical R&D estimates from the US, Canada, Europe, and the Asia-Pacific region from 2007 to 2012. The balance between private and public sector biomedical R&D investments over this period has changed very little: in 2007, the public sector contributed 35.6%, and the private sector 64.4%; in 2012, the mix was 37.1% ($99.6 billion, adjusted for inflation to 2012) and 62.9% ($168.8 billion, adjusted for inflation to 2012), respectively (Chakma et al., 2014). However, the 37.1% contribution by the public sector represents and upper bound, as Chakma et al. define spending by the public sector to include charitable organizations, whereas the G-Finder reports and Røttingen et al. (2013) both recognize the contributions of the philanthropic sector separately.

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[15] "Other Cereals" include buckwheat, fonio, millet, oats, and rye; "Other Pulses" include Bambara beans, broad beans, chick peas, cow peas, lentils, peas, pigeon peas, and vetches; "Other Roots & Tubers" include cassava, sweet potatoes, taro, and yams; "Other Oil-Bearing Crops" include castor oil seed, karate nuts, linseed, melonseed, mustard seed, olives, poppy seed, rapeseed, safflower seed, sesame seed, and sunflower seed; "Other Fruits" include all major fruits except bananas and plantains.
[16] Latest available data for Bangladesh, Pakistan, and Nepal are 2012 not 2014.

According to the 2013 G-Finder report (Moran et al., 2013), the public sector contributed $2.0 billion to neglected disease R&D in 2012, representing roughly 2% of the total 2012 biomedical R&D expenditures of the public sector ($99.6 billion) reported by Chakma et al. (2014). Although the public sector provides the majority of global neglected disease R&D funding, public funding for neglected disease R&D has experienced annual decreases since 2012, and the public sector share of the total dollars spent has decreased from 64% to 61% (Chapman et al., 2016).

4.5 Philanthropic investment in agricultural R&D

Public data on philanthropic funding of agricultural R&D are limited, as philanthropic organizations are not represented in the ASTI database and only the Bill & Melinda Gates Foundation is represented in OECD's Creditor Reporting System. In 2015, the Bill & Melinda Gates Foundation disbursed approximately $153 million for agricultural research in developing countries. From 2009 to 2015, their total contribution amounted to $858m.

Zeigler & Mohanty (2010) report that donors are becoming increasingly interested in agriculture in general as well as agricultural research as a means of alleviating poverty, increasing food security, and attaining economic development in developing countries. Naseem et al. (2011) report that most foundations focus their work on export crops, agribusiness, and other aspects of the commercial sector, which is similar to the focus of the private sector.

Though data are limited, the Bill & Melinda Gates Foundation (BMGF) publicizes its own agricultural R&D expenditures. Between 2003 and 2011, the foundation was responsible for 80 grants funding agricultural R&D in Africa, totaling $642 million. This figure may be an overestimate, however, given grant-based funding often involves multi-year commitments (Spielman, Zaidi, & Flaherty, 2011). The BMGF's top five grant recipients received $244.2 million from 2003 to 2010 for breeding and delivery of improved seed varieties (Gates Foundation, 2011). Three of these five grants, totaling $99.2 million, focus on R&D for maize and wheat. One grant totaling $45 million specifically targets development and delivery of staple crops, including both crops that are more commonly traded (e.g., maize, rice, and wheat) and crops that are generally for subsistence only (e.g., sweet potato, beans, millet, and cassava). The largest grant, totaling $100 million, targets capacity building for both public and private breeding programs in 13 Sub-Saharan African countries.

4.6 Philanthropic investment in health R&D

Among philanthropic organizations, the Wellcome Trust was the largest funder to health R&D in 2013, contributing $909.1 million in funding, followed by the Howard Hughes Medical Institute

($752.0 million), the BMGF ($462.6 million)[18] and Institut Pasteur ($220.9 million) (Viergever & Hendricks, 2016).

In 2015, private foundations contributed $645 million, or 21% of overall R&D funding for neglected diseases (Chapman et al., 2016). This sum represents a large increase in philanthropic spending levels from only $60 million in 1986 (WHO, 2012b). The WHO (2012) attributes this increase largely to the BMGF, which accounts for 80% of all philanthropic spending in 2015 towards neglected disease R&D (Chapman et al., 2016). The second largest funder in 2015 was the Wellcome Trust, and together with the BMGF these two organizations represent 95% of the philanthropic funding for neglected diseases. Without the BMGF investment, philanthropic funding towards neglected diseases would be $127 million; the lowest aggregate funding by sector as well as low proportionally to total R&D funding by sector. As with public and private funding, tuberculosis ($141 million), malaria ($128 million), and HIV/AIDS ($128 million) were the top three philanthropically funded diseases in 2015, representing 62% of philanthropic funding for neglected disease R&D (Chapman et al., 2016).

5   Analyzing R&D provision by type of good and funding source

5.1 Patterns across funders of agricultural R&D

Data on agricultural R&D funding by crop are limited, but the latest ASTI data include a breakdown of the number of public researchers by category of crop for Sub-Saharan Africa and South Asia. These data allow us to further evaluate the hypothesis that public funders will invest more in R&D for subsistence and "orphan" crops, relative to private funders.

Figure 7 presents the number of full-time equivalent (FTE) researchers by crop in Sub-Saharan Africa as well as the production and export value for each category of crops. The largest number of researchers focus on other roots and tubers (besides potatoes), a category of "orphan" crops, and in general the number of "orphan" crops researchers is comparable to that for commodity grains and non-orphan crops. The number of researchers appears to be loosely associated with the production value of different crops (as reported by FAOSTAT). The crops with the highest production values (other roots and tubers and maize) have the highest number of public researchers, and the crops with the lowest number of researchers all have relatively low production values. The figure also indicates that the number of public researchers is not influenced by crop export value. The three crops with the highest export values have among the lowest number of public researchers. This suggests that the public sector in Sub-Saharan Africa may be focusing less on R&D for crops in which the private sector might be more likely to invest.

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[18] Data reflects BMGF spending in 2011 and is reported in 2013 US dollars. Viergever & Hendricks obtained total health research expenditure data for the BMGF from personal communication with a representative from the organization. In contrast, the 2012 G-Finder survey (Moran et al., 2012) reports that in 2011 the BMGF invested about $448 million in neglected diseases (reported in 2007 dollars). This discrepancy may demonstrate differing methodologies for collecting data from the BMGF, as well as varying definitions between health R&D in general and neglected disease R&D in particular.

Figure 7. Public R&D Researchers, Gross Production Value and Export Value by Crop, Sub-Saharan Africa, 2014

Total Researchers, Sub-Saharan Africa   ◆ Production Value, Sub-Saharan Africa

Total Researchers, Sub-Saharan Africa   ◆ Export Value, Sub-Saharan Africa
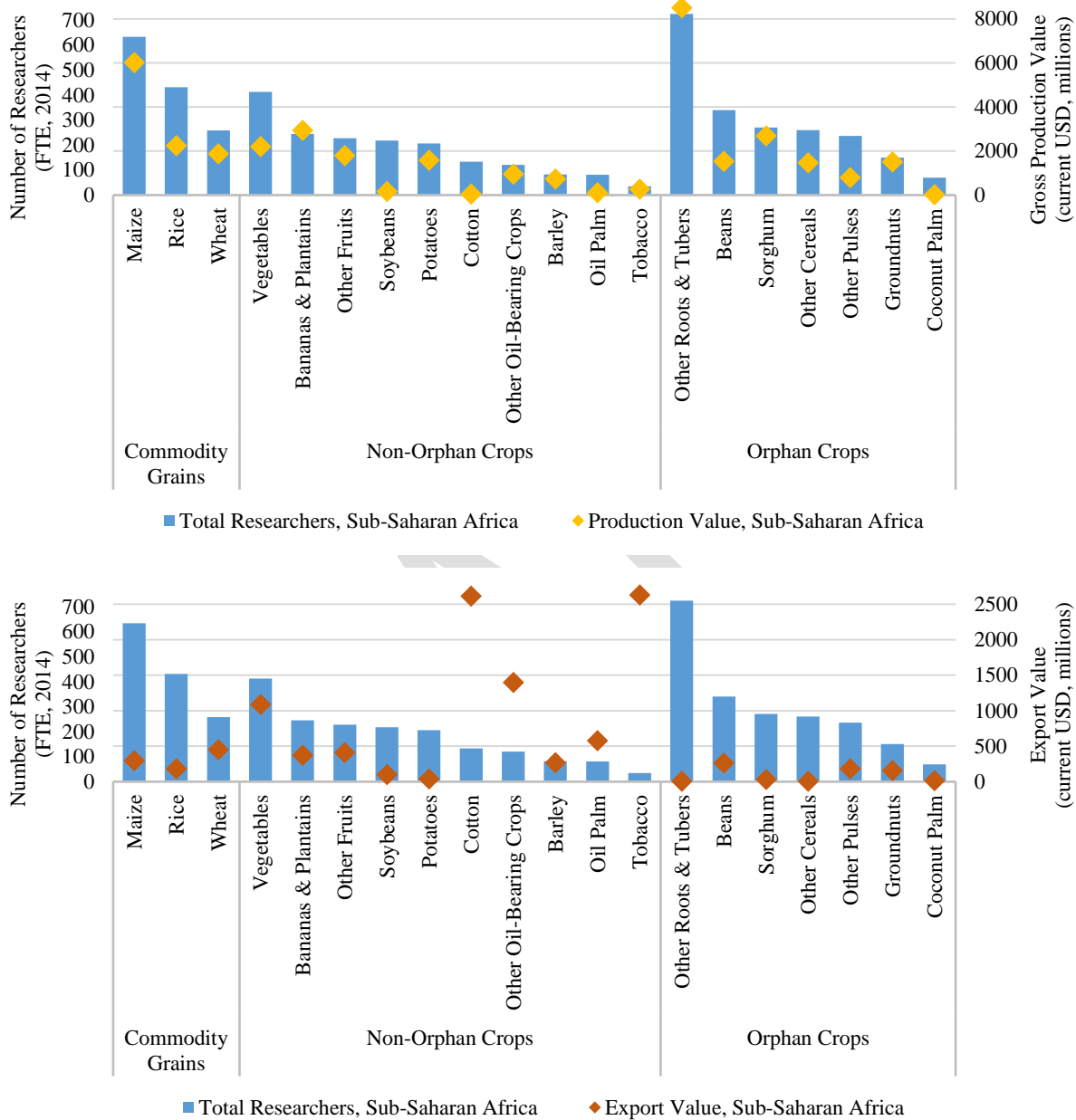
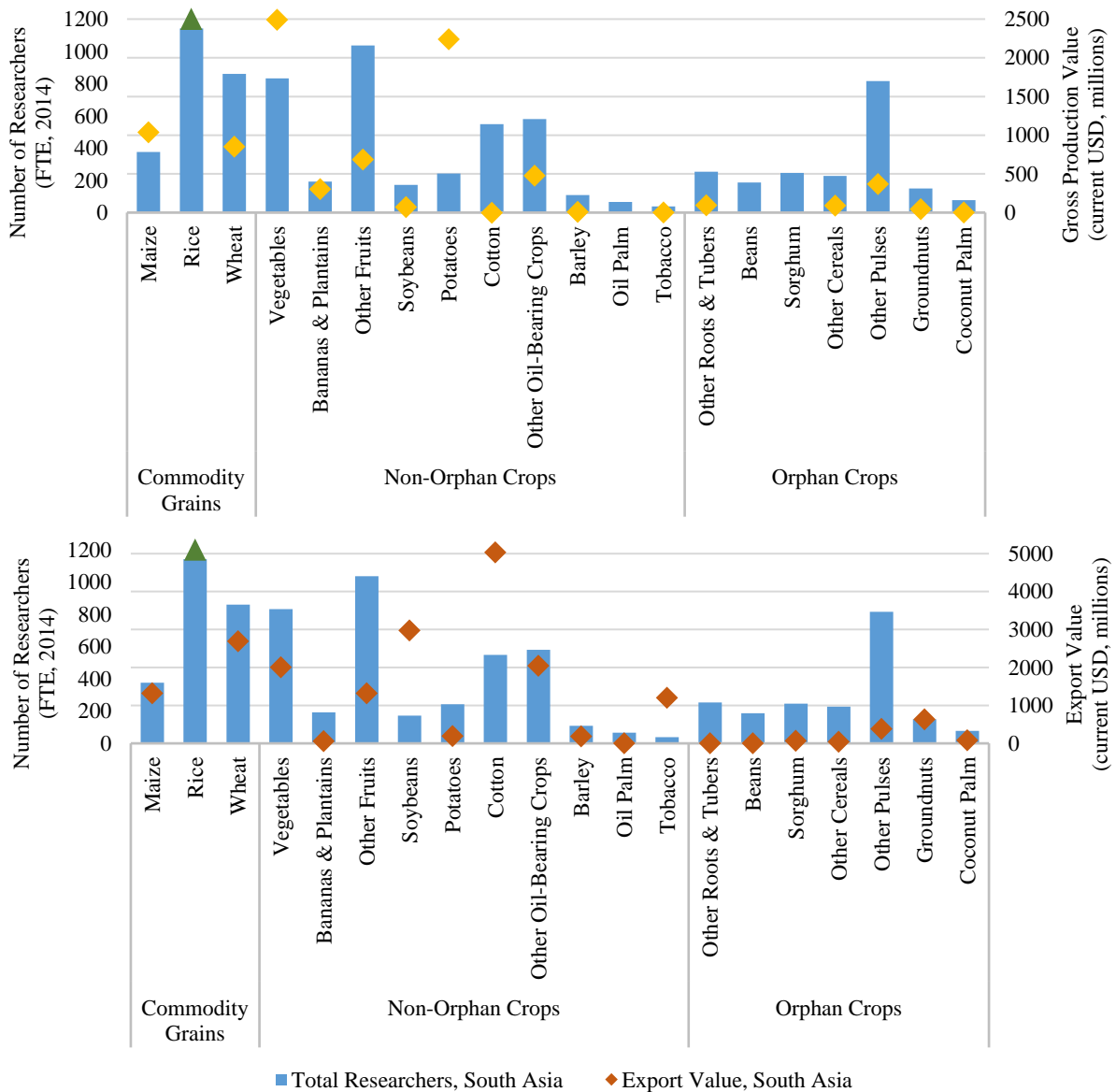*Source:* ASTI Database, 2017; FAOSTAT Statistics Database, 2017

Figure 8 presents that same information for FTE public researchers, crop production value, and crop export value in South and Southeast Asia. As in Sub-Saharan Africa, one category of orphan crops – other pulses (all pulses other than soybeans) – is the focus of a relatively large number of public researchers, and commodity grains also research significant research attention. Unlike in Sub-Saharan Africa, several categories of non-orphan crops have significantly more researchers than orphan crops. Vegetables, other fruits, cotton, and other oil-bearing crops all

have more researchers than any category of orphan crops other than other pulses. This suggests that the public sector in South and Southeast Asia may be investing more in categories of agricultural R&D that could be funded by the private sector.

We also observe a limited association between production value and public research attention. Rice has the highest production value and the most researchers, but vegetables and especially potatoes appear to have much lower research attention relative to their production value, while other fruits and other pulses appear to have relatively high research attention accounting for their production value. The number of cotton and soybeans researchers appears primarily driven by the export value of these crops, but otherwise it is not clear that crop export value is associated with public research FTE allocation.

Figure 8. Public R&D Researchers Gross Production Value and Export Value by Crop, South Asia, 2014

5.2 Patterns across funders of health R&D

Trouiller et al. (2002) review global drug development from 1975 to 1999, and find that the distribution of the new chemical entities in different therapeutic areas is biased towards high-income countries, a bias which is magnified for infectious and parasitic diseases. The authors find that these diseases represent one-third of the global disease burden, but only 5% of the disease burden in high-income countries. Of the total 1393 new chemical entities brought to market during this time, only 16 were for tropical diseases and tuberculosis, and all depended on public-sector investment for their development (*ibid.*).

Unlike for global health R&D overall, the public and philanthropic sectors provide a greater share of funding for neglected diseases, as expected due to the lower potential financial returns from R&D targeting these diseases. Public sources provided 63% of the global total of funding for neglected disease R&D in 2015, compared to 21% from philanthropic sources and 15% from the private sector (Chapman et al., 2016). Overall spending on neglected diseases in 2015 was $3.041 billion (*ibid.*), a small proportion of the total invested in health R&D. In 2009, neglected disease R&D funding was approximately 1% of total health R&D funding (Jamison et al., 2013).

Drawing on data for neglected disease spending in 2009 from the 2010 G-Finder report (Moran et al., 2010) and Røttingen et al. (2013)'s estimates of funding by sector for total health R&D from the subset of mainly high-income countries for which disaggregation by sector was possible (representing 90% of total global R&D funding), we estimated the share of funding by sector allocated to neglected diseases. Based on these estimates, we find that the private sector allocated approximately 0.3% of health R&D funding to neglected diseases, compared to 3.3% for the public sector and 3% for the philanthropic sector. The public and philanthropic sectors therefore allocated about 10 times more of their funding to neglected diseases than the private sector, relative to their total health R&D funding, supporting our second hypothesis.

To evaluate whether public and philanthropic investments in neglected disease R&D are associated with potential social benefits, we compare funding flows for select neglected diseases by sector against estimates of the burden of disease for each disease as measured by DALYs. DALY estimates are taken from the Global Burden of Disease 2015 report, as reported in the 2016 G-Finder report (Chapman et al., 2016) on neglected disease funding.
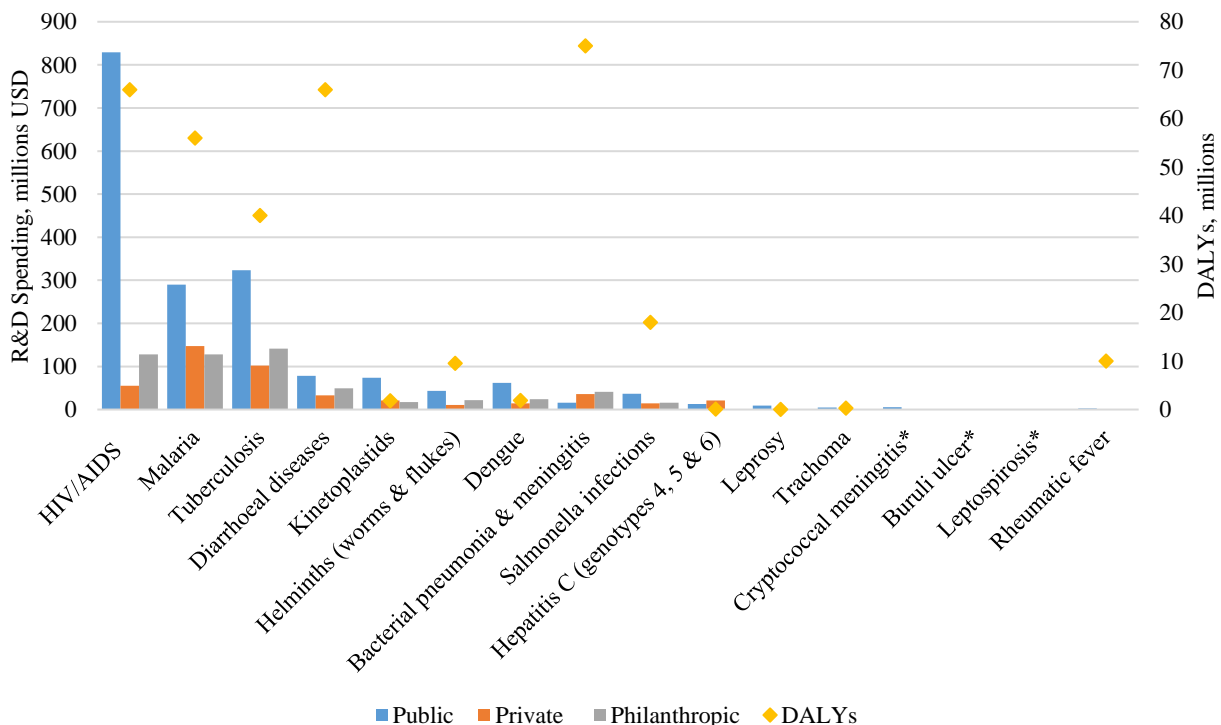
As illustrated in Figure 9, the "big three" infectious diseases were the most well-funded of the neglected diseases by a wide margin in 2015, receiving $2.144 billion or 71% of all neglected disease R&D funding (Chapman et al., 2016). Private sector investments focus on the "big three", likely because these diseases have some levels of incidence in higher-income countries. The "big three" infectious diseases were also the top publicly-funded neglected diseases in 2015, receiving $1.442 billion, or 75% of all public funding for neglected disease R&D. The high level

of spending may in part reflect the large burden of DALYs due to these diseases, with HIV/AIDS responsible for 66 million DALYs in 2015, compared to 56 million from malaria and 40 million from tuberculosis. However, both diarrheal diseases and pneumonia and meningitis resulted in more DALYs in 2015 than the "big three", but neither of these categories of diseases received much R&D funding.

Public funding for individual neglected disease R&D does not appear to closely track DALYs. HIV/AIDS received 43% of total public funding for neglected diseases compared to only 4% for diarrheal diseases, though both caused approximately the same number of DALYs in 2015. Kinetoplastids resulted in 1.8 million DALYs in 2015, but received more public R&D funding than helminths (9.5 million DALYs), bacterial pneumonia and meningitis (75 million DALYs), salmonella (18 million DALYs), and rheumatic fever (10 million DALYs) (Chapman et al., 2016).

This lack of alignment can be due to DALYs being only one factor of R&D investments. The pathogenic complexity of certain diseases or the availability of an effective treatment may affect funding amounts. Helminths, for example, has an effective presumptive treatment while Kinetoplastids has a relatively ineffective and toxic treatment.

**Figure 9. Public, Private, and Philanthropic Neglected Disease R&D Spending and DALYs, 2015**

Source: Chapman et al., 2016
* Information on 2015 DALYs not available

Figure 10 presents 2015 data on funding for neglected disease R&D excluding the "big three" infectious diseases (Moran et al., 2009). The figure illustrates that while public sources provide the majority of R&D funding for most neglected diseases, private sources provide most funding for hepatitis C. These data focus on hepatitis C genotypes incident in developing countries, but the nature of hepatitis C research is such that research on one genotype may relate to research on other genotypes and eventually lead to a pan-genotypic therapy. This private sector focus on these neglected hepatitis C genotypes may in fact be due to the incidence of other hepatitis C genotypes—and thus a market for treatments—in developed countries.

Figure 10. Public, Private, and Philanthropic Neglected Disease R&D Spending and DALYs, 2015, Excluding "Big Three" Infectious Diseases
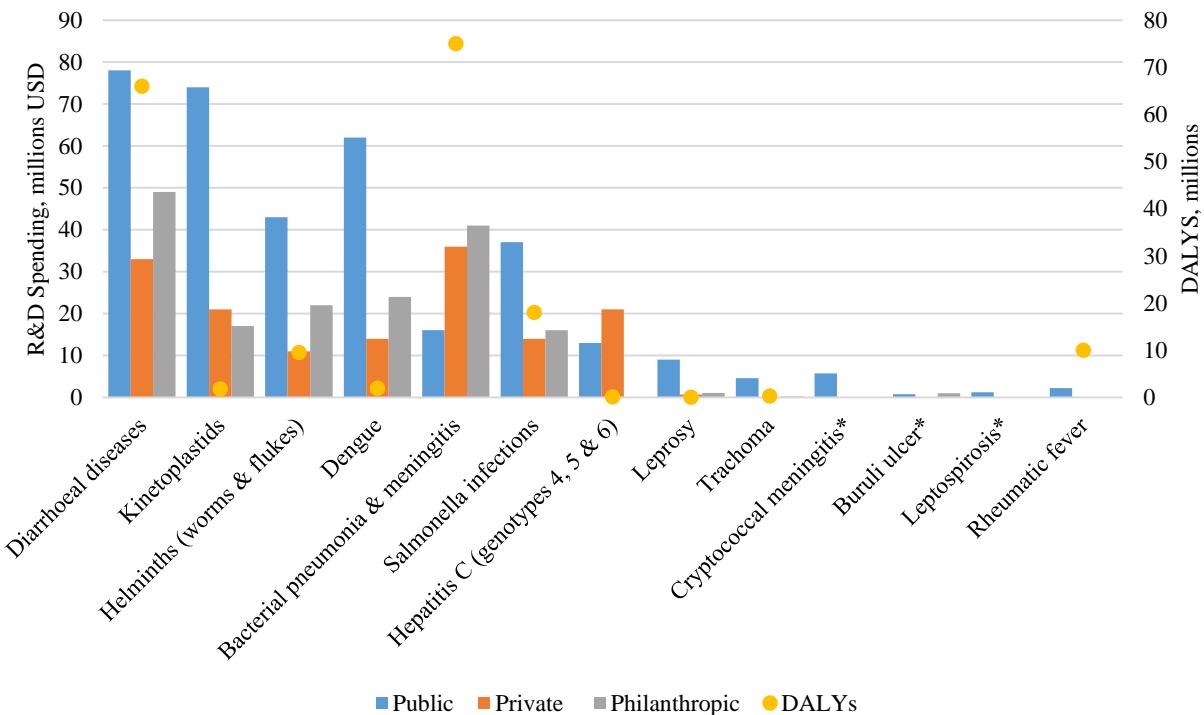
Source: Chapman et al., 2016
* Information on 2015 DALYs not available

6   Discussion

In this analysis, we compared R&D funding across sectors of investors to broad categories of crops and diseases, focusing on differences between the sectors in the relative importance of financial versus social returns and on differences between the categories of R&D in the potential of obtaining financial returns. In reality, the calculus is likely much more nuanced, and will vary by the type of health and agricultural R&D and by investor. The degree and type of risk, for example, that different investors will tolerate is likely to vary, as is their acceptable time horizon. There may be economies of scale and scope associated with R&D (Naseem, 2010), and revenue calculations will consider growth vs. contraction, local delivery systems, distribution of capital

assets, etc. Finally, this model does not include how costs, revenues, risk, or timing are affected by cross-sector partnerships. To the extent that any sector has a comparative advantage investing in a particular phase or product, partnerships (with each partner engaging in the activity in which they are the low cost investor) can increase the efficiency of producing goods.

Sagasti & Bezanson (2001) contend that public sources (including ODA, developing country budgets, and funds from international agencies) have an advantage from economies of scale, with expertise across multiple sectors. Spielman, Hartwich, and Grebmer (2010) argue that public-private partnerships capitalize on organizational knowledge by bringing together diverse areas of expertise. In the case of technologically-based agricultural research, private industry often has a significant lead over public institutions in facilities and experience, meaning joint public-private sector research could be speedier and more efficient than public research alone (Qaim et al., 2000). Partnerships between public funders (for example, national governments and international organizations) are also argued to improve efficiency through synergy (Pingali, 2010). Mustapha et al. (2014) argue that public-private partnerships and "blended finance" often increase the net impact of public funding, as "every unit of donor money attracts non-grant funds which are several times higher than the original donor investment". Echeverria & Beintema (2009) contend that foundations can "play a catalytic role in bringing together public and private initiatives and so positively influence technology transfer and training of producers" (p. 11).

In addition to the within sector complexities, we also acknowledge that agriculture and health are entirely different. For example, products based on health R&D are likely to have greater scalability than products based on agricultural R&D. This is because vaccines can be effective for individuals across the world, while seeds must be tailored to individual agro-ecological contexts.

Nonetheless, broad patterns are distinguishable and we discuss these in the contexts of our main hypotheses: that public and philanthropic funders, relative to the private sector, would provide more R&D funding for crops and diseases where investments were viable if social benefits were considered – including orphan crops and neglected diseases. Our findings for agricultural R&D at best offer mixed support for these hypotheses. Our findings for health R&D more so.

Consistent with our expectations, the bulk of empirical evidence to date indicates that private R&D funding for agriculture focuses on market-oriented crops, for which net returns in domestic and international markets are higher. Private R&D in agriculture is concentrated in cash crops, such as hybrid varieties of rice and maize, palm oil, rubber, tea, vegetables, horticulture, and improved livestock (Morris, 1998; Morris, Singh, & Pal, 1998; Pray & Fuglie, 2001; Gerpacio, 2003; Naseem et al., 2010). Very little private funding goes to subsistence cereal crops like sorghum, barley, or millet, roots and tubers such as potatoes, sweet potatoes, yams, and cassava, and other underutilized crop species (National Research Council, 1996, 2006, 2008; Padulosi et al., 2002; Gruere, Giuliani, & Smale, 2006; Naseem et al., 2010).

Similarly, the bulk of empirical evidence to date indicates that private R&D funding for health focuses on diseases with greater incidence in developed countries, for which net returns in

domestic and international markets are higher. In health, the private sector funds the majority (60%) of overall R&D (Røttingen et al., 2013), but less than 1% of all private funding for health R&D goes to neglected diseases (Jamison et al., 2013). Our review suggests that among neglected diseases private sector R&D funding largely targets the "big three" infectious diseases which are relatively more common in high- and middle-income countries unlike the other diseases categorized as "neglected" by G-Finder (Moran et al., 2009).

Most of the global investments in basic agricultural R&D since the 1980s have been funded by the public sector (Echeverria & Beintema, 2009; Pingali, 2010). We find some evidence that public spending and research efforts target orphan crops otherwise neglected by scientific research, especially roots and tubers in Sub-Saharan Africa (the largest single category of public research funding in Sub-Saharan Africa) and pulses other than soybeans in South and Southeast Asia. These subsistence crops have a moderate to large number of researchers allocated to them, but they also have a far greater production value than many of the commodity or cash crops which – contrary to what a theoretical efficient global planner would decide – appear to be attracting substantial public research funding in spite of their market (private sector) orientation (CGIAR, 2017; FAOSTAT 2017).

The most heavily internationally traded crops – cotton and tobacco – receive less public funding relative to cash crops like oil crops (which notably also have important domestic markets in Sub-Saharan Africa). This pattern in cash crops funding may suggest that in some instances the public sector is investing less in export-oriented cash crops precisely because these crops are more suited to private investment, consistent with our theoretical expectations (though these findings may be skewed by the lower production levels of cash crops compared to cereals). However, some of the most well-funded crops in both Sub-Saharan Africa and South and Southeast Asia are rice, maize, and wheat, and major cash crops including vegetables and oil crops – and in this respect it appears from available data that large portions of public agricultural R&D spending are allocated to crops with greater potential for private investment, perhaps speaking to the financial, social, and food security value of staple cereal crops, or their share of local, regional, or international markets. But to the extent that this prioritization comes at the expense of less-traded orphan subsistence crops, which receive less public R&D money but may have higher marginal social benefits from R&D investment, it challenges hypothesis one.

We find that philanthropic organizations and public sources provide a much larger share of R&D funding for neglected diseases (85%) than the private sector (Chapman et al., 2016), though the large majority of all sector funding goes to diseases other than neglected diseases. We also compared neglected disease R&D funding allocations to a non-market metric of funding need, the DALYs due to individual diseases. Among the neglected diseases reviewed in G-Finder (Chapman et al., 2016), funding is only weakly associated with DALYs, with public funding low relative to DALYs for diarrheal diseases, bacterial pneumonia/meningitis, salmonella, and worms/flukes. Private sector funding allocations differ markedly from public sector allocations, concentrated largely on the "big three" infectious diseases but also prominent for diarrheal diseases, bacterial pneumonia/meningitis, and hepatitis C, where public funding is relatively low (suggesting specialization by one or both funders). Philanthropic funding largely follows public

funding, except for HIV/AIDS and Ebola where it is proportionately much lower, and rheumatic fever, for which it provides nearly 90% of R&D funding. Thus, although public and philanthropic sources of funding do have a much greater focus on neglected disease R&D than private sources, it is not clear that public and philanthropic funding allocations are driven by social returns as measured by DALYs.

Finally, the observed overlap across sector spending especially noted in agricultural R&D may reflect public and philanthropic sources prioritizing spending on areas that promote or facilitate private sector involvement. Although uncertainty is in our model and certainly part of decision-making, we don't test for risk differentials across sectors, crops or diseases. Yet within developing counties, private spending on R&D is likely limited by risks related to weak regulatory institutions and poor infrastructure (Gerpacio, 2003; Pray & Naseem, 2003; Echeverria & Beintema, 2009). Some authors suggest that philanthropic foundations have an advantage funding high-risk projects (Pratt et al., 2012; Mondiale, 2001), and can play an important role in catalyzing public and private investment (Echeverria & Beintema, 2009). To the extent that public-private partnerships are becoming more common in R&D (Spielman, Hartwich, & Gerbmer, 2010; Ferroni & Castle, 2011; Woodson, 2016) and that there are also high social returns to R&D for commodity crops and for general health, we might expect some degree of overlap in the spending of public, private, and philanthropic sources. Indeed some authors suggest that public-private partnerships may be a method to increase private investment in general R&D and in research for less profitable crops (Brow, 2008; Kharas & MacArthur, 2014) and neglected diseases (Wheeler & Berkley, 2001; WHO, 2015; Woodson, 2016).

As low-income countries develop, we might predict that in more developed markets with greater willingness to pay for improved seed varieties or new drugs and reduced risk from weak regulatory institutions or infrastructure, differences between private and public allocations of R&D spending would be more evident. We observe some potential evidence of this in relatively wealthier developing countries, where the private sector has taken a prominent role in R&D for some key agricultural commodities. Gerpacio (2003) reports that the private sector captured nearly 90% of the Asian maize seed market in the late 1990s and early 2000s, and Narrod & Fuglie (2000) report that in 2000, that 99% of Brazilian, 81% of Thai, 70% of Phillipine, and 62% of Indian poultry were derived from breeds developed by less than ten private firms, all of which were based in developed countries. In more developed or higher-income countries, therefore, it may be more likely that public agricultural R&D spending will go towards crops not already targeted by private spending. For health R&D, we might expect that private sector spending would be greater in countries where patent regimes allow private companies to capture a greater share of the returns from their research, freeing up public and philanthropic spending for other "neglected" diseases. We observe that private funding for neglected diseases, while small compared to overall private health R&D spending, is concentrated on the "big three" diseases which offer greater potential financial returns due to their greater incidence in high-income countries.

Other parameters in our model – such as locational preferences and discount rates – appear untestable with currently available data. Given more data, we might test whether public sector government funders, relative to private and philanthropic funders, are more likely to fund agricultural and health R&D with greater potential returns for their domestic constituents, and whether public multilateral investors and philanthropic investors are more likely to fund R&D with greater returns for low-income populations. Future research could consider whether funding allocations by source differ between high-income and low-income countries or countries with different regulatory and property rights institutions. What seems evident is that current tracking and data are insufficient to allow a global planner to recommend allocations for R&D funding based on relative advantage.

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