

STUCK ON STUBBLE? THE NON-MARKET VALUE OF AGRICULTURAL BYPRODUCTS FOR DIVERSIFIED FARMERS IN MOROCCO*

NICHOLAS MAGNAN^a, DOUGLAS M. LARSON^b, AND J. EDWARD TAYLOR^b

Diversified agricultural households often use byproducts of one activity as inputs for another. For crop-livestock farmers, cereal production provides grain and crop residue, where the latter can be used as livestock feed. To properly assess the cost of introducing new technologies into such systems, one must value the implicit cost of byproducts, which is made difficult by missing byproduct markets. We estimate the shadow value of non-market crop stubble using household data from Morocco and find that stubble accounts for around one-quarter of the value of cereal production in a normal rainfall year and three quarters in a drought year.

Key words: Crop-livestock systems, shadow value, technology adoption, no-till.

JEL codes: O13, Q12, Q24.

Materials or energy produced as a byproduct of one production process often are used as inputs for another. In some cases producers can leverage this relationship through trade (Lowe 1997). If market imperfections prevent byproduct trade, firms can take advantage of economies of scope by internalizing byproduct transactions (Teece 1982). This type of internalization is very common in agriculture, especially in developing countries, where transaction costs are high and there are other benefits of diversification, e.g., risk management and

wealth storage in the absence of financial markets (Barrett, et al. 2001; Bromley and Chavas 1989).

The most widespread example of diversification in agriculture is mixed crop-livestock farming, or more specifically cereal-livestock farming. A commonly employed definition of a crop-livestock system is one in which at least 10 percent of dry matter fed to livestock comes from crop byproducts and at least 10 percent of the total value of production comes from non-livestock farming activities (Seré and Steinfeld 1996). Complementarities in crop-livestock systems include using manure as fertilizer, manure or crop residue as fuel, crop residue as bedding or building material, and most commonly, crop residue as livestock feed. Crop-livestock systems are widespread and provide livelihoods to many millions of people. They account for close to 50 percent of the world's cereals (and most of the cereal consumed by the poor), 75 percent of the world's milk, and 50–60 percent of the world's meat. Nearly 70 percent of the world's ruminant population resides in crop-livestock systems (Herrero, et al. 2010; Steinfeld, et al. 2006). The importance of crop residue as an input for livestock production therefore has implications for crop and technology choices that affect economic development and agricultural sustainability on a very large scale.

*This article is derived from the first author's dissertation completed at UC-Davis. We are deeply grateful to Erika Meng, without whom this project would not have happened. We miss her dearly. We also thank, without implication, Aden Aw-Hassan, Abdelaziz Chergaoui, Azeddine El Brahli, Aziz Fadlaoui, Yoko Kusunose, Rachid Mrabet, and enumerators and support staff at INRA-Meknès. Aslihan Arslan, Steve Boucher, Michael Carter, Jim Chalfant, Travis Lybbert, and participants at various seminars and conferences all provided valuable input. An anonymous referee and the editor provided insightful and helpful comments. All remaining errors are our own. This work was generously funded by USAID Linkage Grants between UC-Davis and both CIMMYT and ICARDA, and by the Graduate School and College of Agricultural and Environmental Sciences at UC-Davis.

^aCorresponding author. Department of Agricultural and Applied Economics, 315 C Conner Hall, University of Georgia, Athens, GA 30602 USA.

Email: n.magnan@cgiar.org, phone: (202) 467-8177, fax: (202) 467-4439.

^bDepartment of Agricultural and Resource Economics, University of California, Davis; Giannini Foundation of Agricultural Economics.

Farmers who adopt no-till (NT) cereal production reduce the amount of residue available as livestock feed because some stubble must be kept on the field after each harvest. This reduction may contribute to low adoption rates for NT and related resource conserving technologies among small farmers in developing countries, despite these methods' well-documented potential to increase and stabilize yields, lower fuel costs, prevent erosion, and mitigate climate change through carbon sequestration (Erenstein 2003; Mrabet 2008; Pieri, et al. 2002).¹

The importance of crop residue as feed also has implications for cereal variety choice. Many of the high-yielding dwarf varieties developed during the Green Revolution divert biomass from residue to grain production. Such varieties may seem superior to plant breeders, who generally do not place a value on residue production, but might not be adopted where the value of residue is relatively high compared to that of grain (Rao and Hall 2003; Traxler and Byerlee 1993). Similarly, a reduction in residue availability could discourage conversion from cereal to high-value cash crop (HVC) production, a potential pathway by which small farmers can escape poverty and sequester carbon. Because HVCs do not always produce byproducts that can be used as feed, the profit gap between HVCs and cereals may be smaller when the value of crop residue is accounted for. Certain harvesting technologies could also be rejected because they render residue unsuitable as feed, as was the case for an imported peanut harvester in Senegal (International Fund for Agricultural Development 1998).

Although crop-livestock complementarities are widely recognized, to our knowledge the value of crop residue has not been rigorously and fully quantified, even though this value could represent a significant deterrent to the adoption of new technologies and crops. The value of straw—residue that can be removed from the field, transported, and marketed—is usually observable through local market prices. Valuing stubble, residue grazed directly from the field after straw removal, is more difficult. Generally no market price for stubble exists, so a shadow price must be used. A shadow price is the household's decision price, formed

internally by household supply and demand for a non-market good (De Janvry, et al. 1991; Singh, et al. 1986). In this article we develop a household crop-livestock farming model to estimate the shadow price of crop stubble using unique panel data from Morocco.

Morocco is an ideal setting in which to test our model. Cereal production, mostly of wheat and barley, is widespread, accounting for about 70 percent of agricultural land (Food and Agriculture Organization 2009). The use of cereal residue as livestock feed in Morocco is omnipresent and substantial; an estimated 30–40 percent of biomass in the average ruminant's diet comes from cereal residue, although this percentage can be higher or lower for individual herds. In arid and semiarid cereal growing regions of Morocco, crop stubble typically is the sole source of feed in the summer and fall months following the harvest (Nordblom and Shomo 1993; Tarhzouti, et al. 2006).

The high prevalence of crop residue in livestock diets is not unique to Morocco or the Mediterranean region. Rao and Hall (2003) estimate that crop residue composes 40–60 percent of livestock diets in India; Renard (1997) estimates 41 percent in Bangladesh, 51 percent in Nepal, and 46 percent in Pakistan; Keftasa (1988) estimates 40–50 percent in Ethiopia; and Nordblom and Shomo (1993) estimate 13 percent in Sudan. In a multi-country survey of crop-livestock farming in Asia and Latin America, McDowell and Hildebrand (1980) find estimates ranging from 30–90 percent, and Thornton and Herrero (2010) posit that throughout the developing world residues compose up to 50 percent of livestock diets. While these studies estimate the biomass of residue consumed by livestock, no study we are aware of measures the value of this biomass, which is ultimately what influences farmers' technology decisions.

As in much of the developing world, NT adoption in Morocco has been rare, and traditional cereal production still dominates among small farmers, despite strong institutional will to advance NT and encourage HVC production. A multitude of NT field trials conducted over the past 30 years have been highly successful from an agronomic point of view (Mrabet 2008), and NT is a component of the recent National Plan against Global Warming. Meanwhile, HVC expansion is the centerpiece of an ongoing \$300 million cooperative project between the Millennium Challenge Corporation and the Moroccan

¹ No-till and its variations are also referred to as conservation agriculture, zero-till, minimum-till, reduced-till, and conservation-till. Throughout this article we use the term no-till, abbreviated as NT.

government to improve and expand fruit tree production, with expansion aimed at land currently used for cereal production.² In a separate effort, the government of Morocco plans to help farmers convert 3 million ha. of marginal cereal land to market-oriented HVCs to combat rural poverty. Despite the perceived benefits of NT and HVC production, few farmers have embraced these changes. To understand the barriers to adoption that mixed cereal-livestock farmers face, it is necessary to quantify the full value of crop residue as livestock feed.

Straw generally has a local market price and is therefore relatively easy to value. Stubble, however, is challenging to value because it is not traded and has no market price; thus, its price is a shadow price.³ To estimate the shadow price of stubble we develop a structural model from the crop-livestock farmer's constrained profit maximization problem, from which we estimate shadow prices for individual farmers. Because of endogeneity concerns, we leverage the panel nature of the data by using a farmer fixed-effects model to estimate the livestock production function.

We find that in a normal rainfall year, the shadow value of crop stubble accounts for around one-quarter of the total value of cereal production, on average.⁴ In a drought year, when grain production is very low and livestock feed is scarce, the shadow value of crop stubble accounts for three-quarters of the total value of cereal production. The large difference in value between years highlights the role of residue as a risk buffer. In both a normal year and drought year the implicit cost of not using crop stubble as feed outweighs the estimated annual cost savings from NT adoption in the study region.

We regress household-level shadow value estimates on household characteristics and find that farmers with less land and less land in cereal derive more value per hectare of crop stubble than farmers with more land and more land in cereal. Our results also suggest that farmers who are able to enforce property rights over crop stubble on their land derive more value from this resource, and the shadow value

of stubble varies substantially across the three agro-climatic zones covered by our study.

Theoretical framework

Because data on crop residue consumption normally are not collected, existing studies estimate the prevalence of residue in livestock diets from aggregate cereal production and aggregate herd data using conversion parameters (Nordblom and Shomo 1993; Rao and Hall 2003; Smil 1999). Although this approach might be appropriate for estimating the total mass of crop residue used as feed by the aggregate of all farmers in a given area, this method does not lend itself well to calculating the value of crop residue consumed, because it does not differentiate straw from stubble or consider how much residue individual farmers' herds consume.

Making the jump from the quantity of straw produced by a given farmer to the value of that straw is straightforward, because farmers can privatize straw production, local market prices for straw exist, and production data are obtainable. This is not true for stubble. The amount of stubble a farmer feeds his herd cannot necessarily be measured by the amount of cereal he harvests.⁵ Because of enforcement costs, traditions, or social norms, crop-livestock farmers in developing countries often graze their herds on other farmers' stubble (Erenstein 2003; Lesorogol 2010; Pieri, et al. 2002). This phenomenon is evident in our study area; half of farmers reported grazing their livestock on other farmers' stubble.

Even if crop stubble consumption were observable in terms of biomass, several important differences between straw and stubble would make calculating the value of this biomass challenging. During harvest, grain is knocked off the stalk onto the ground amidst the stubble, rendering stubble more nutritive than straw (personal communication with Abdelaziz Chergaoui, August 2007; Thomas, et al. 2010). However, livestock may need to expend a considerable amount of energy to graze stubble compared to straw and other portable feed sources. Furthermore, the timing of stubble consumption is inflexible compared to storable feed sources, as grazing must occur shortly after the harvest (Tarhzouti, et al. 2006; Thomas, et al. 2010). For these reasons, we

² For details see <http://www.mcc.gov/pages/countries/program/morocco-compact>.

³ In extremely rare instances in the study region stubble grazing rights are traded, but prices vary widely as markets are not at all well established. Lesorogol (2010) also finds anecdotal evidence of farmers selling stubble grazing rights in northern Kenya.

⁴ In this article we use "shadow price" to describe the marginal per-unit implicit value of stubble and "shadow value" to describe the total implicit cost of some quantity of stubble, i.e., shadow price times quantity.

⁵ We employ masculine pronouns throughout because 100 percent of household heads in our sample are male.

model stubble consumption at the herd level as opposed to stubble production at the farm or more aggregate level. This allows us to quantify tradeoffs between the use of crop stubble and market feed by exploiting differences in feed usage between farmers and across years.

Farmers in the study region use a combination of market and non-market feeds to maintain their herds. Some market feeds—straw, hay, and barley grain—are either produced on-farm or bought at market. Others—maize, commercial concentrate, and processing-level agricultural byproducts such as dried beet pulp and bran—are acquired nearly exclusively at market. To simplify the analysis, we assume that farmers do not face constraints on liquidity or availability of market inputs. We also assume that farmers face zero transaction costs for market feed, so that consuming feed produced on-farm is equivalent to purchasing it. In reality, liquidity constraints, limited market availability, and transaction costs likely influence the feed bundle farmers choose. Although we do not incorporate these market imperfections into our empirical analysis, we later discuss how they would affect our results.

Non-market feed sources—crop stubble, grasses on fallow land, permanent pasture, and green forage (forage crops grazed before harvest)—are grazed directly off the ground and have no market price. Farmers are quantity constrained for these inputs, but they are not price constrained. For our analysis we aggregate feed sources up to the following categories: (1) straw, (2) hay, (3) high-grade feed, (4) stubble, (5) pasture and fallow grasses (“grass” hereafter), and (6) green forage.

Jacoby (1993) and Skoufias (1994) use a household production model to estimate the shadow price of a non-market agricultural input, household labor, using the price of a market output as a reference. This technique is also implemented by Sonoda and Maruyama (1999) and Abdulai and Regmi (2000) to estimate the shadow price of labor. Arslan and Taylor (2009) turn this approach on its head to estimate the shadow price of a non-market agricultural output, subsistence maize, using the price of market labor as a reference. We estimate the shadow price of a non-market input for livestock production, crop stubble, using the price of a market input as a reference. Our approach is similar to Le (2009), who uses the price of a market input, fertilizer, as a reference to derive the shadow price of non-market labor. Because we use the market price of an input as a reference, we do not

need price data on the output, which can be either a non-market good or a market good for which prices are unobservable. This methodology is useful for dealing with livestock, because observed sales prices are idiosyncratic and livestock is not so much produced over the course of a year as it is maintained.

We begin by solving a constrained profit-maximization problem that results in a system of factor demand equations. From this system we derive the shadow price of crop stubble. A farmer maximizes profit by maintaining a herd of size H using some combination of feed sources \mathbf{z} , where z_j is the quantity of feed source j . Feed sources $j = 1 \dots m$ are market feeds and are traded at prices \mathbf{w} . Feed sources $j = m + 1 \dots M$ are non-market feeds and can be used without paying out of pocket ($w_j = 0$ for $j = m + 1 \dots M$), but their consumption is limited by availability, \mathbf{z}^{max} . The livestock maintenance function is defined generally as $H = g(\mathbf{z})$. The farmer’s profit-maximization problem can be written as

$$(1) \quad \max_{\mathbf{z}} \quad \lambda \cdot g(\mathbf{z}) - \mathbf{w} \cdot \mathbf{z}$$

$$\text{s.t.} \quad z_j \leq z_j^{max} \text{ for } j = m + 1 \dots M.$$

The associated Lagrangian function can be written as:

$$(2) \quad L = \lambda \cdot g(\mathbf{z}) - \sum_{j=1}^m w_j \cdot z_j$$

$$- \sum_{j=m+1}^M \rho_j \cdot (z_j - z_j^{max})$$

The parameter λ is the value to the farmer of maintaining an additional unit of livestock for one year, and ρ_j is the shadow price of non-market input $j = m + 1 \dots M$. First order conditions for (2) with respect to \mathbf{z} can be interpreted as the inverse demand functions for market feeds, $w_j = \lambda \cdot \frac{\partial g(\mathbf{z})}{\partial z_j}$ for $j = 1 \dots m$, and for non-market feeds, $\rho_j = \lambda \cdot \frac{\partial g(\mathbf{z})}{\partial z_j}$ for $j = m + 1 \dots M$. Assuming that $g(\mathbf{z})$ is increasing in z_j , it must be true that $z_j = z_j^{max}$ for $j = m + 1 \dots M$. This is a reasonable assumption; in the study region, very little crop stubble goes unclaimed.

Farmers choose inputs in any year so that the price ratio of any two feeds equals the marginal productivity ratio of those feeds, regardless of herd size or λ . It is therefore not necessary to assume that H and λ are time-invariant for

a given farmer. Shadow prices adjust so that the shadow price of non-market feed k is the amount of market feed j required to compensate for the loss of one unit of k times the market price of j , i.e.,

$$(3) \quad \rho_k = \lambda \cdot \frac{\partial g(\mathbf{z})}{\partial z_k} = w_j \cdot \frac{\frac{\partial g(\mathbf{z})}{\partial z_k}}{\frac{\partial g(\mathbf{z})}{\partial z_j}}$$

for $j = 1 \dots m$, $k = m + 1 \dots M$.

We call feed j the reference market input. If $m > 1$ then there are multiple reference market inputs to choose from, and the choice of which one to use may hinge on quality and completeness of data (Arslan and Taylor 2009; Le 2009). In our empirical application we estimate the shadow price of stubble using two different market feeds as references.

Data

Data are from a survey conducted during the summers of 2007 and 2008 in the Middle Atlas Region of Morocco. The survey was administered orally to a randomly selected sample of farmers in three distinct zones: urban fringe, low plains, and foothills. The main cereals grown in this region are soft wheat, durum wheat, and barley, and cereal production is mostly rainfed. Wheat is used solely as food and barley as both food and feed. Livestock predominantly consists of sheep but also includes cows and goats. Many households also keep several equines for traction or transport. Farmers generally give all species in their herds the same type of feed, especially in the case of small ruminants.

Five to six villages were randomly selected within each zone for a total of 16 villages. Within each village, 16 households were randomly selected from village rosters.⁶ An average of 14 households per village completed the survey in 2007. In total 223 households were surveyed in 2007, and 206 of the same households were resurveyed in 2008. The data include information on a variety of activities, including cereal and livestock production. Livestock data include an animal inventory and detailed accounting of feed use. Feed prices

⁶ In addition to the 16 "first choice" households, four "back-up" households were randomly selected from each village roster. When a household head from the list of 16 could not be found for interview, a pre-selected back-up household was used.

Table 1. Area Cultivated and Livestock Holdings by Year

Variable	N	2007	2008	P-value
Cultivated area (ha.)	203	8.28 (8.46)	7.81 (8.09)	0.57
Cereal area (ha.)	203	6.65 (7.31)	5.73 (5.60)	0.16
Sheep	205	30.70 (52.15)	37.05 (91.46)	0.39
Cows	205	3.40 (2.73)	3.79 (3.04)	0.18
Goats	205	3.28 (17.17)	6.04 (26.35)	0.21
Equines	205	1.49 (1.74)	2.41 (9.02)	0.15
TLU	205	6.83 (8.06)	8.33 (10.95)	0.12

Notes: Standard deviations in parenthesis. P-value is for t-test of difference between years.

were gathered via a village survey. A rather unique feature of the data is that they contain information on non-market feed use, specifically, how long livestock (by animal type) grazed on the farmer's own crop stubble, other farmers' stubble, grass, and green forage.

Mean cultivated area in the sample is around 8 ha. In each year of the survey, an average of just over three-quarters of cultivated land was planted in cereals or forage crops. Other crops cultivated include legumes, tree crops, and vegetables. Households had an average herd size of 33 sheep, 4.6 goats, 3.5 bovines, and 1.9 equines. To aggregate across livestock types, we employ the tropical livestock unit (TLU), assigning a weight of 0.1 TLU for each sheep or goat and 0.7 TLU for each bovine or equine (Food and Agriculture Organization 1999). Mean herd size was 7.4 TLU and was 18 percent smaller in 2007 than 2008; however, the difference in TLU between the two survey years is not statistically significant. Table 1 contains descriptive statistics on farm and herd size by year.

The use of crop stubble as livestock feed is ubiquitous in the study region. The survey data indicate that nearly 95 percent of households use crop stubble as feed; 45 percent of farmers use only stubble on their own land, 45 percent use stubble on their own and other farmers' land, and four percent use only stubble on other farmers' land. Because farmers do not exclusively graze livestock on their own plots and many graze other farmers' plots, they usually

Table 2. Feed Source Use by Year

Feed	Variable	N	2007	2008	P-value
Straw	% using	189	0.96	0.97	0.22
	Bales (15 kg)		464.4 (449.1)	226.4 (192.5)	0.00**
Hay	% using	189	0.57	0.48	0.11
	Bales (15 kg)		209.3 (431.5)	79.13 (224.7)	0.00**
High-grade feed	% using	189	0.87	0.82	0.54
	100 kg bags		28.37 (73.54)	16.20 (25.90)	0.04*
Stubble	% using	189	0.95	0.94	0.76
	LWD		1093 (1526)	1546 (2405)	0.02*
Grass	% using	189	0.45	0.68	0.00**
	LWD		892.8 (2175)	1755 (3314)	0.00**
Green forage	% using	189	0.57	0.56	0.77
	LWD		690.6 (1387)	905.1 (1563)	0.13

Notes: Sample includes only households with livestock in both years.

Standard deviations in parenthesis. P-values are for t-tests of differences across years; **denotes $p < 0.01$, *denotes $p < 0.05$.

do not know the area of crop stubble on which they graze their herds. However, they do know approximately how long they graze their animals on crop stubble on their own and other farmers' land. On average, farmers grazed their herds on stubble for 71 days.⁷ The unit we use to measure stubble demand is the livestock-weighted day (LWD) of grazing. For instance, a farmer who grazes 2 cows and 6 sheep (2 TLUs) on stubble for 60 days uses 120 LWDs of stubble. We employ the same measure for grass and green-forage grazing.

Data from 2007 refer to the 2006–2007 agricultural year (August 2006 to July 2007), and data from 2008 refer to the 2007–2008 agricultural year. On average, farmers were able to graze their herds on crop stubble for longer in the normal rainfall year of 2008 (1,546 LWDs) than in drought-plagued 2007 (1,093 LWDs). Low rainfall in 2007 also led to reduced biomass availability on pasture and fallow land. Consequently, farmers grazed an average of 1,755 LWDs of grass in 2008, compared with 893 LWDs in 2007.

To compensate for lower non-market feed availability, farmers demanded greater quantities of market feed in 2007 than in 2008. More than 95 percent of farmers used straw during

both years, but the quantity of straw used in 2007 was twice that used in 2008. In 2008 (2007), 48 (57) percent of farmers reported using hay and 82 (87) percent reported using high-grade feed, although the differences between the number of users across years are not significant. However, the average quantity of hay used was 2.5 times greater in 2007 than in 2008, and the average quantity of high-grade feed used in 2007 was nearly twice the amount used in 2008. Table 2 contains descriptive statistics on feed use by year.

These inter-year differences in feed use suggest that farmers substitute market for non-market feed in response to drought. Farmers also may alter their herd size between the two years due to the dearth of non-market feed. However, regardless of herd size, equation (3) must hold. That consumption of all market feeds is greater in the drought year suggests that straw alone is not a substitute for stubble and grass, as Steinfeld et al. (2006) report. In the following section, we analyze the tradeoffs between different feed sources in order to calculate the shadow price of stubble.

Estimation and Results

In order to estimate marginal productivities of different feed sources, we must choose a functional form that makes the profit-maximization problem in (1) tractable. The Cobb-Douglas

⁷ The question was posed as “over what months do you graze your herd on _____”, and the answer was converted to days. While this conversion would inflate the number of days for farmers who grazed over partial months we see no reason to believe this inflation would be systematic.

function allows for decreasing marginal input productivity while being easy to work with, because it is linear in logs. For these reasons, it is often chosen to calculate marginal productivities from household production functions (Abdulai and Regmi 2000; Arslan and Taylor 2009; Jacoby 1993; Le 2009; Skoufias 1994; Sonoda and Maruyama 1999). Using Cobb-Douglas also allows us to impose constant returns to scale, which we assume throughout.⁸ Because of observations of zero input use, we follow the common practice of adding 1 to all inputs and outputs and therefore must omit observations with zero values for stubble or the reference market feed from the regressions.

In both study years, straw and stubble were each used by more than 94 percent of farmers. By comparison, 82 to 87 percent used high-grade feed, and 48 to 57 percent used hay, making straw appear to be the best reference feed to use. However, it is possible that high transaction costs prevent some farmers from participating in straw markets, causing their shadow price of straw to deviate from the market price. For farmers who buy straw, or those who would buy straw absent transaction costs, the shadow price of straw may exceed the market price. Stubble shadow prices calculated using the market price of straw as a reference then would be downward biased. Farmers who sell straw or those who would sell straw absent transaction costs might choose either to store straw or feed more straw to their livestock than would be optimal otherwise. For these farmers, stubble shadow prices calculated using straw as a reference would be upward biased.

Few farmers in the study are straw autarkic. In 2008, 56 percent of farmers reported using more straw than they produced, and 32 percent reported using less. However, only 45 percent of farmers reported buying straw in 2008, suggesting that some farmers stockpile excess straw for later use, a phenomenon evidenced by visible straw stocks in the study region. The majority of farmers who used more straw than they produced in 2008 participated in straw markets, but nearly one fifth did not.⁹

⁸ Because there are no fixed factors of livestock production in the model (e.g., land, labor, or management), doubling all variable inputs (feed) should double the number of heads of livestock a farmer can maintain.

⁹ We only have data on straw purchases from 2008, and do not have data on straw sales from either year.

As the robustness check, we use high-grade feed as a reference market feed. High-grade feed sources—dried beet pulp, commercial concentrate, maize, and bran—are nearly exclusively purchased at market. Barley grain can be produced on-farm but is much easier to transact than straw. In our sample, 70 percent of farmers reported buying high-grade feed, and 85 percent of high-grade feed users participated in high-grade feed markets. Although market feed provides a useful robustness check, it is possible that liquidity constraints cause the shadow prices of market feed sources to be higher than market prices. We do not have sufficient data on liquidity to handle this issue empirically, but we return to it conceptually while discussing our results.

Household production functions are often estimated using cross sectional data, and endogeneity concerns are typically addressed using instrumental variables (Abdulai and Regmi 2000; Arslan and Taylor 2009; Jacoby 1993; Le 2009; Sonoda and Maruyama 1999). Because we have panel data, we can use a farmer fixed-effects model specification similar to Skoufias (1994) to control for unobservable farmer heterogeneity that may influence both input use and production. In this study, heterogeneity would likely manifest itself as unobserved differences in livestock quality. While the data include livestock quantity broken down by species and in some cases gender as well as some sale prices, they do not include animal weight, age, or the market value of unsold animals, which likely differ systematically from the value of sold animals. If herd quality is correlated with unobserved variables that also influence factor demand, production function estimates may be biased.

Consider the case of a farmer with underweight livestock because liquidity constraints prevent him from purchasing high-quality animals. The same liquidity constraints could prevent him from providing market feed for his herd. If initial herd quality is not controlled for, the model will overvalue this farmer's herd by assuming it is of average quality. If the animals are overvalued, so will be the marginal productivities of the inputs used to maintain the them. If farmers with poor quality livestock systematically use relatively more stubble than market feed, stubble will be overvalued.

We can alter the model to include unobservable animal quality or weight c_i as a farmer specific adjustment to $g(z)$. When logs are taken the maintenance function is linear in log

livestock and feed quantities, i.e.,

$$(4) \quad \log(g_{it}) + \log(c_i) = \log(A) + \sum_{j=1}^M \alpha_j \cdot \log(z_{jit}) + v_{it},$$

The error term in (4), v_{it} , can be decomposed as $v_{it} = \mu_i + \tau_t + \varepsilon_{it}$, where μ_i is a farmer fixed-effect, τ_t is a year fixed-effect, and ε_{it} is a random disturbance term. We mean-center the data so that the time-invariant unobserved quality terms, $\log(c_i)$ and μ_i , drop out of the model, leaving

$$(5) \quad \Delta \log(g_{it}) = \sum_{j=1}^M \alpha_j \cdot \Delta \log(z_{jit}) + \tau_t + \varepsilon_{it}.$$

For a fixed-effects model to be consistent, the error term ε_{it} must be orthogonal to the mean-centered explanatory variables in $\Delta \log(z_{it})$. This is equivalent to saying ε_{it} in either period must be uncorrelated with the input quantities for both periods, which is a stronger assumption than that of no contemporaneous correlation. One could argue that feed given to the herd in one period might affect a farmer's ability to maintain his animals in the next period, i.e., a farmer could overfeed livestock during a year of plenty and maintain the herd the following year while feeding it less. We assume that current herd size does not depend on feed given in previous or future years.

We estimate (5) using a farmer fixed-effects model (FE), in which the constant term τ_t amounts to a year effect. To estimate (4), we assume $c_i = 1$ and use OLS with pooled data with (OLS I) and without (OLS II) control variables and village fixed-effects. Controls include age and education of the household head, household size, and total land area. We first use straw as the reference feed, then use high grade feed. In both cases we must omit observations for which the farmer does not use any of the reference feed.¹⁰ The term $\frac{\hat{\alpha}_{stubble}}{\hat{\alpha}_j}$ for $j = \{\text{straw, high-grade}\}$ is a non-linear combination

of parameter estimates for which the standard errors can be calculated by linear approximation or by bootstrapping (Krinsky and Robb 1986). As is generally the case, we find bootstrapped standard errors to be more conservative than linear approximations, and we report them in our results.

Using either straw or high-grade feed as the reference market feed, we find estimates of $\frac{\hat{\alpha}_{stubble}}{\hat{\alpha}_j}$ to be robust across model specifications.

In both cases, the point estimate obtained using OLS I is higher than the FE estimate, suggesting that unobservable farmer heterogeneity leads to slightly upward biased estimates of the shadow price of stubble when using OLS without controls. However, because the OLS II estimate is nearly identical to the FE estimate using either market feed as a reference, it seems that most heterogeneity can be controlled for by accounting for time-invariant observable farmer characteristics and village fixed-effects. Regression results for the livestock maintenance function can be found in table 3.

To check that our empirical model returns plausible maintenance function estimates, we can compare the cost of maintaining additional livestock using straw to the cost of doing so using high-grade feed. If the estimates are plausible, costs should be similar across feed sources. Using median values of herd size, feed use, and feed prices from the pooled data, our estimates of $\hat{\alpha}_{straw}$ and $\hat{\alpha}_{high-grade}$ imply that maintaining an additional sheep for one year requires either 396 kg of straw valued at 449 Dh or 115 kg of high-grade feed valued at 380 Dh ($\$1US = approx. 8Dh$).¹¹ We can also compare the caloric requirements implied by our econometric results to those documented elsewhere for maintenance of a female sheep: 1480 kcal per day (Boulanouar and Paquay 2006, p 302). Using calorie conversion factors for straw and high-grade feed (barley in this case), we find that 270 kg of straw per year or 161 kg of barley per year satisfies this requirement.¹²

¹⁰ Estimates of $\hat{\alpha}_{straw}$ ($\hat{\alpha}_{high-grade}$) are robust across the three specifications using straw (high-grade feed) as the reference feed. Because coefficient estimates for variables with zero values are sensitive to the choice of constant added before taking logs, we cannot reliably estimate $\hat{\alpha}_{straw}$ ($\hat{\alpha}_{high-grade}$) using data from the subset of farmers who did not all use straw (high-grade feed). We therefore estimate $\hat{\alpha}_{stubble}/\hat{\alpha}_{straw}$ ($\hat{\alpha}_{stubble}/\hat{\alpha}_{high-grade}$) using only observations for farmers who used both stubble and straw (high-grade feed).

¹¹ A more formal approach to testing the overidentification restriction—within the noise of the data—is to test the null hypothesis of equality of marginal cost relative to marginal productivity across reference feed sources. Using a t-test to compare these ratios, we cannot not reject the null for $p = 0.15$ using the pooled data, which suggests the model reflects optimizing behavior reasonably well. We thank an anonymous referee for suggesting this test.

¹² Most sheep in our sample were female. To calculate kilocalories per kg of straw we refer to information provided

Table 3. Livestock Maintenance Function Estimates

TLU	Straw			High-grade		
	FE	OLS I	OLS II	FE	OLS I	OLS II
Straw (15 kg bales)	0.227** (0.032)	0.177** (0.029)	0.236** (0.032)	0.114** (0.038)	0.080** (0.027)	0.101** (0.028)
Hay (15 kg bales)	0.009 (0.010)	0.014 (0.009)	0.007 (0.009)	0.007 (0.012)	0.024* (0.010)	0.006 (0.011)
High-grade feed (100 kg)	0.063** (0.024)	0.143** (0.025)	0.076** (0.018)	0.214** (0.045)	0.183** (0.030)	0.199** (0.029)
Stubble (LWD)	0.674** (0.037)	0.658** (0.038)	0.679** (0.036)	0.648** (0.044)	0.709** (0.038)	0.696** (0.040)
Grass (LWD)	0.027** (0.009)	0.004 (0.007)	0.004 (0.006)	0.011 (0.011)	0.004 (0.008)	0.000 (0.008)
Green forage (LWD)	0.000 (0.008)	0.003 (0.007)	-0.002 (0.006)	0.006 (0.012)	-0.000 (0.007)	-0.003 (0.007)
$\hat{\alpha}_{stubble}/\hat{\alpha}_{straw}$	2.823** (0.879)	3.652** (0.680)	2.876** (0.567)			
$\hat{\alpha}_{stubble}/\hat{\alpha}_{high-grade}$				3.206** (1.199)	3.874** (0.877)	3.495** (0.815)
Year 2007		0.011 (0.056)	-0.053 (0.057)		0.072 (0.055)	0.051 (0.059)
Controls $p < 0.05$?			Yes			Yes
Village FE $p < 0.05$?			Yes			Yes
Constant		-4.143** (0.133)	-4.431** (0.219)		-4.076** (0.146)	-4.262** (0.240)
R-squared	0.084	0.781	0.817	0.074	0.784	0.813
Observations	324	368	368	248	323	323

Notes: Only farmers using both stubble and market feed $j = \{\text{straw, high-grade}\}$ are included in regressions. Household cluster robust standard errors (bootstrapped for $\hat{\alpha}_{stubble}/\hat{\alpha}_j$) are in parentheses; ** denotes $p < 0.01$, * denotes $p < 0.05$. R-squared shown is the coefficient of determination.

Solving (3) using the maintenance function parameter estimates gives the estimated shadow price of stubble as $\hat{\rho}_{stubble,i} = \frac{\hat{\alpha}_{stubble}}{\hat{\alpha}_j} \cdot \frac{z_{j,i}}{z_{stubble,i}} \cdot w_{j,i}$. Because $\frac{\hat{\alpha}_{stubble}}{\hat{\alpha}_j}$ is constant across farmers, the median (mean) shadow prices for the sample are equivalent to the shadow prices for a representative farmer as determined by the median (mean) ratio of stubble to market feed j used. Given that input ratios can become very large when one input, in this case crop stubble, is used in very small quantities, we calculate mean shadow prices excluding the top and bottom 2.5 percent of the distribution.

Using feed demand data from both years and FE estimates of $\frac{\hat{\alpha}_{stubble}}{\hat{\alpha}_j}$, we find that the median (mean) shadow price of stubble is 17.2 (30.1) Dh per LWD using straw as the reference market feed and 14.9 (25.8) Dh using high-grade feed. The differences between median and mean estimates are not unexpected, inasmuch as the distributions of ratios frequently have long right tails. Thus, while both measures are informative, the medians are a better measure of central tendency because they are not sensitive to high skews like those present in our data.

Stubble availability differs from year to year in our data set; thus, the shadow price also would be expected to differ, in the opposite direction of the change in quantity. That is what we find: The median and mean shadow prices of stubble are two to three times higher in the drought year of 2007 than in 2008. Table 4 presents estimates for the shadow price of stubble under the FE specification using both straw and high-grade feed as the reference market feed; OLS II estimates (not shown) are 1-9 percent higher.

by North Dakota State University available at http://www.ag.ndsu.edu/disaster/drought/documents/FeedingStraw_000.pdf, and an online energy converter provided by UC-Davis available at <http://animalscience.ucdavis.edu/java/LivestockSystemMgt/Conversion/energy.htm>. We use barley as the reference high grade feed and refer to information provided by the government of Alberta and available at [http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/sg4843](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sg4843) to calculate kilocalories per kg of barley.

Table 4. Estimated Shadow Prices of Crop Stubble

Dh/LWD	Pooled		2007		2008	
	(Straw)	(High-grade)	(Straw)	(High-grade)	(Straw)	(High-grade)
Median	17.20	14.88	27.87	23.60	8.52	7.78
Mean	30.10	25.83	49.26	37.87	13.59	14.94
Std. error	2.09	2.01	4.04	3.93	1.01	1.64
N	324	248	162	124	162	124

Notes: Shadow prices derived using fixed-effects maintenance function estimates. **denotes $p < 0.01$, *denotes $p < 0.05$ for significance of difference between years.

Table 5. Decomposed of Value of Cereal Production per Hectare

		Value (Dh)			Proportion of total		
		Pooled	2007	2008	Pooled	2007	2008
Grain	Median	1,535	612.5	2,886**	0.35	0.13	0.57**
	Mean	2,280	1,106	3,616**	0.35	0.18	0.54**
Straw	Median	480.0	300.0	801.3**	0.11	0.06	0.14
	Mean	816.1	570.2	1,072**	0.13	0.10	0.16
Stubble	Median	1,768	2,823	1,140**	0.48	0.76	0.24**
	Mean	3,928	4,991	2,918**	0.53	0.72	0.30**
All residue	Median	2,687	3,024	1,936*	0.65	0.87	0.43**
	Mean	4,743	5,561	3,954**	0.65	0.82	0.46*

Notes: Includes only farmers with both crops and livestock. **denotes $p < 0.01$, *denotes $p < 0.05$ for significance of difference between years.

The Economic Importance of Stubble

Our estimation results indicate that the median shadow price of stubble was around 8 Dh (\$1.00) per LWD in the normal rainfall year of 2008 and between 23 and 28 Dh (\$2.90 to \$3.50) per LWD in the drought year of 2007. How substantial is this implicit cost of stubble? When farmers consider technologies that reduce or eliminate the use of stubble as feed or supplant cereal altogether, they logically take into account the opportunity cost. There is a deterrent to adoption if the value of stubble is high compared to the total value of cereal production or to the benefits of a new technology.

We compared the shadow value of crop stubble to the value of other cereal co-products and to the potential cost savings offered by NT. Then we regressed farmer-specific shadow value estimates onto household characteristics to explore which farmers are most likely to be deterred from adopting certain technologies by high stubble use-value. We combined plot-level yield data and village-level price data for the three major grains grown in the region—soft wheat, durum wheat, and barley—to calculate the value of grain production per hectare for each farmer in each year. We performed the same calculation to obtain the market value of

straw produced per hectare. Because farmers do not always graze their own plots, it is difficult to capture the total amount of grazing a plot provides. However, what ultimately is most important from the perspective of private returns is the amount of grazing that a plot provides to its owner, so this is the amount we use in our analysis.

The shadow value of stubble generated per hectare of cereal production is the product of the number of LWDs a farmer gets from one hectare of stubble and the farmer's shadow price of crop stubble. This approach is analogous to the common practice of multiplying the shadow wage times the number of hours worked to calculate shadow income (Abdulai and Regmi 2000; Jacoby 1993; Le 2009; Skoufias 1994), and it is the most appropriate way to make comparisons with other per hectare production values.¹³ The total value of cereal production is the sum of grain market value, straw market value, and stubble shadow value. For our analysis, we use the shadow price of stubble estimated using straw as the reference market feed. Results of these calculations can be found in table 5.

¹³ Calculating the integral of the shadow price over the quantity used would yield an infinite value.

After the drought-plagued campaign of 2007, 43 percent of farmers reported achieving zero grain yields, compared to only 4 percent in 2008. Farmers who did harvest some grain in 2007 reported yields half as large as in 2008. As a result, the median value of grain production was 613 Dh/ha. in 2007 and 2,886 Dh/ha. in 2008. The median value of straw production was also lower in 2007 (300 Dh) than in 2008 (801 Dh).

Due to scarcity, the average shadow value of stubble produced per hectare was greater in 2007 than 2008, even though the quantity grazed was less. Using the shadow price estimates, we find that the median value of stubble production was 2,823 Dh/ha. in 2007, compared to 1,140 Dh/ha. in 2008. Stubble accounted for a median of 76 percent of the total value of cereal production in 2007 and 24 percent in 2008. Total residue—straw and stubble combined—accounted for 87 percent of the total value of production in 2007 and 43 percent in 2008.¹⁴

These values for stubble and total residue may seem high, but they are not inconsistent with qualitative findings. Bradford (1999) notes that farmers in sheep-cereal systems in the Middle East and North Africa perceive stubble and straw to be at least as important as grain production, particularly because in drought years farmers will generate some livestock feed even if there is no grain harvest. Similar observations have been made in South Asia (Kelley, et al. 1993). The high shadow value of crop residue in the drought year of our study highlights one way in which crop-livestock farmers self-insure through diversification.

Our findings suggest that the shadow value of crop stubble is a formidable barrier to NT adoption. Estimates from the study indicate that costs can be reduced by 250–450 Dh/ha. using NT as a result of eliminating plowing. This is equivalent to a 7–13 percent decrease in total costs (Magnan, et al. 2011). Such savings pale in comparison to the average value of crop stubble, even in a normal rainfall year. Although Mrabet (2002) finds that 30 percent of crop stubble can be removed without jeopardizing yields, the shadow value of the remaining

70 percent still offsets the potential cost-saving aspects of NT (450 Dh/ha) for 100 percent of farmers in the drought year and 75 percent in the normal rainfall year.

The benefits of NT go beyond reducing production costs. By using NT, farmers can increase and stabilize yields and improve soil structure to sustain productivity into the future (Erenstein 2003; Mrabet 2008; Pieri, et al. 2002). However, these complex long-term productivity and environmental benefits might not be readily apparent to farmers, particularly those who are liquidity constrained in the short-run. If farmers base their adoption decision primarily on short-term benefits and costs, NT is unlikely to be as attractive when the shadow value of stubble is considered. Likewise, crop-livestock farmers choosing between cereal and HVCs that do not generate residue will consider the high value of crop residue.

Differences in stubble valuation across farmers

Crop stubble constitutes a substantial portion of the total value of cereal production to the crop-livestock farmers in the study sample. But to whom is it most valuable and thus a stronger deterrent to NT and HVC adoption? We regressed stubble value per hectare onto farmer and farm characteristics. In this regression, we use stubble value per hectare as opposed to total stubble value, because the net benefit of adopting NT or HVCs is most easily thought of in per-hectare terms. Explanatory variables include age and education of the household head, household size, herd size, total area farmed, percent of farmed area in cereal, and a dummy variable for the drought year of 2007. We include zone fixed-effects to account for unobserved farm and farmer characteristics common to a given zone. Because the dependent variable, the per-hectare shadow value of stubble, is estimated rather than observed, we bootstrap standard errors (Dumont, et al. 2005), re-sampling pairs to account for the panel nature of the data.

In one set of specifications we include a dummy variable indicating whether or not the farmer reported exercising exclusive grazing rights on the majority of his stubble. In 2007, two-thirds of farmers reported exclusively grazing stubble on their own plots, whereas in 2008 one-third did. Some farmers grazed exclusively only in 2007, whereas others did so only in 2008. Admittedly, exclusive grazing is potentially endogenous because

¹⁴ One reason the value of stubble is particularly high compared to the value of straw in drought years is that when farmers do not harvest their grain, straw is likely to be diverted to stubble because there is little incentive to remove the straw as opposed to grazing it directly.

the farmer can choose to enforce property rights over stubble depending on the scarcity of the resource. However, because we have no satisfactory instrument for this variable, we assume exogeneity and interpret the results with caution.

Our results indicate that farmers with less land and farmers who have a lower percentage of land in cereals derive more value per hectare of stubble. We do not find that herd size or composition (results not shown) have a significant effect on the stubble shadow value. It follows that small farmers and farmers with less cereal face a larger barrier to adopting technologies that reduce stubble production or availability. Indeed, in developing countries worldwide, NT adoption rates are particularly low among small farmers (Pieri, et al. 2002). While there are many reasons why this might be true, our results indicate that a relatively high implicit cost of stubble could be one of them.

We find that households derive more value from their stubble when they graze it exclusively. Although not surprising, this finding suggests that farmers who can exclude others from grazing their stubble when not practicing NT face a higher barrier to NT adoption than farmers who cannot. However, for farmers who would not be able to prevent others from grazing all of their stubble while practicing NT the adoption question is moot. HVC farmers presumably would not generate crop stubble, so the opportunity cost of replacing cereal with HVCs would be higher for farmers who can exercise property rights.

Zone fixed-effects are highly significant, revealing that households in the plains and foothills derive less value from stubble than farmers on the urban fringe. This finding suggests that extension services in the study region aimed at encouraging NT (and possibly HVCs) should set their targets farther away from the urban area, where the opportunity cost is lower. Estimation results can be found in table 6.

Transaction Costs and Other Market Failures

The results we present in this article assume that the market price of market feeds is the farmer's decision price. It is possible, however, that transaction costs or liquidity/credit constraints put a wedge between market and shadow prices of market feeds. For a liquidity-constrained farmer, equation (2)

Table 6. Determinants of Shadow Value of Stubble Production

Value of stubble (Dh/ha)	(1)	(2)
Age of household head	21.20 (29.01)	20.96 (31.38)
Education of household head	-14.49 (319.7)	21.46 (337.6)
Household size	-140.8 (149.5)	-1, 360 (124.3)
Herd size (TLU)	15.68 (21.67)	13.67 (22.13)
Total area farmed (ha.)	-92.05** (22.51)	-91.90** (25.11)
Land in cereals (%)	-3, 177** (814.6)	-3, 206** (1, 149)
Year 2007	2, 416** (487.96)	2, 043** (521.16)
Plains zone dummy	-5, 317** (1, 072)	-5, 094** (956.4)
Foothills zone dummy	-5, 664** (1, 047)	-5, 707** (959.3)
Exclusively grazes own stubble		1, 156* (519.4)
Constant	9, 030** (1, 880)	8, 721** (1, 842)
R-squared	0.310	0.318
Observations	332	332

Notes: Bootstrapped standard errors in parentheses; **denotes $p < 0.01$, *denotes $p < 0.05$.

becomes:

$$(6) \quad L = \lambda \cdot g(\mathbf{z}) - \sum_{j=1}^m w_j \cdot z_j - \sum_{j=m+1}^M \rho_j \cdot (z_j - z_j^{max}) - \gamma \cdot \left(\sum_{j=1}^m w_j \cdot z_j - B \right),$$

where B is a budget constraint, γ is the cost of liquidity, and $\gamma > 0$ if $\sum_{j=1}^m w_j \cdot z_j = B$, that is, if the farmer is liquidity constrained. The shadow price of z_k in this case is:

$$(7) \quad \rho_k = (1 + \gamma) \cdot w_j \cdot \frac{\frac{\partial g(\mathbf{z})}{\partial z_k}}{\frac{\partial g(\mathbf{z})}{\partial z_j}} \text{ for } j = 1 \dots m, \\ k = m + 1 \dots M$$

Because we do not observe B and therefore cannot measure γ with our data, we underestimate the shadow price of stubble for liquidity constrained farmers. Our estimates should therefore be viewed as a lower bound; in an environment with severe liquidity constraints, the shadow price of stubble will pose an even greater barrier to the adoption of certain technologies.

Potential shadow-price estimation biases due to market failures are not unique to this study. Jacoby (1993), Skoufias (1994), and Abdulai and Regmi (1999) all depend on the assumption of perfect markets for the agricultural goods produced by small farmers. Arslan and Taylor (2009) depend on the assumption that perfect markets exist for labor used to produce a subsistence crop. Le (2009) assumes that there are perfect markets for fertilizer and no liquidity/credit constraints that would prevent its purchase. The assumption of at least one well-functioning market is necessary if one wishes to use a household production model to calculate the shadow price of a non-market good. The researcher is responsible for determining what good most likely fits that description and for considering what a market failure for that good might imply for shadow price estimates.

Conclusions

Diversified agricultural households in developing countries often use non-tradable byproducts of one production activity as inputs for other activities. Nowhere are these economies of scope more visible than in crop-livestock systems, which produce more than half of the world's cereal, meat, and milk and provide livelihoods for many millions of people. Because crop and livestock production are intertwined, proponents of technologies that impact one activity must consider the whole system. Failure to quantify the value of non-market byproducts may lead researchers, development practitioners, and policymakers to miscalculate the benefits of new technologies.

Our findings from Morocco indicate that the shadow value of crop stubble for small crop-livestock farmers is substantial: In our sample, stubble accounts for around one-quarter of the total value of cereal production in a normal rainfall year and around three-quarters in a drought year, when many farmers harvest little to no grain. The high shadow value of

stubble in the drought year highlights one way in which crop-livestock farmers self-insure through diversification.

These findings highlight the economic importance of residue by-products to small farmers in crop-livestock systems. They reveal that the opportunity cost of alternative land uses that preclude stubble production or its use as feed are substantial. This creates a powerful deterrent to shifting into relatively high-value cash crops or using crop residue for soil conservation rather than as feed. For most farmers in our sample, the shadow value of stubble is greater than the cost-saving benefits of adopting no-till, a resource conserving technology that has experienced slow uptake despite having many demonstrated benefits. We find that the shadow value of stubble produced per hectare is greater for farmers who are small, have less land in cereal production, and are closer to the urban periphery. For these farmers, a high shadow value of stubble represents a significant deterrent to the adoption of technologies that reduce stubble availability. Governments and NGOs would do well to heed these findings while designing programs to promote no-till agriculture or cash crops as a means of raising agricultural incomes, combating poverty, or conserving soils.

References

- Abdulai, A., and P. Regmi. 2000. "Estimating Labor Supply of Farm Households under Nonseparability: Empirical Evidence from Nepal." *Agricultural Economics* 22(3):309–320.
- Arslan, A., and J.E. Taylor. 2009. "Farmers' Subjective Valuation of Subsistence Crops: The Case of Traditional Maize in Mexico." *American Journal of Agricultural Economics* 91(4):956.
- Barrett, C.B., T. Reardon, and P. Webb. 2001. "Nonfarm Income Diversification and Household Livelihood Strategies in Rural Africa: Concepts, Dynamics, and Policy Implications." *Food policy* 26(4):315–331.
- Bradford, G. 1999. "Contributions of Animal Agriculture to Meeting Global Human Food Demand." *Livestock Production Science* 59(2–3):95–112.
- Bromley, D.W., and J.P. Chavas. 1989. "On Risk, Transactions, and Economic Development in the Semiarid Tropics." *Economic Development and Cultural Change* 37(4): 719–736.

- De Janvry, A., M. Fafchamps, and E. Sadoulet. 1991. "Peasant Household Behaviour with Missing Markets: Some Paradoxes Explained." *The Economic Journal* 101(409):1400–1417.
- Dumont, M., G. Rayp, O. Thas, and P. Willemé. 2005. "Correcting Standard Errors in Two-Stage Estimation Procedures with Generated Regressands." *Oxford Bulletin of Economics and Statistics* 67(3): 421–433.
- Erenstein, O. 2003. "Smallholder Conservation Farming in the Tropics and Sub-Tropics: A Guide to the Development and Dissemination of Mulching with Crop Residues and Cover Crops." *Agriculture, Ecosystems & Environment* 100(1):17–37.
- Food and Agriculture Organization. 2009. Faostat. <http://faostat.fao.org>.
- . 1999. "Livestock and Environment Toolbox." <http://www.fao.org/ag/againfo/programmes/en/lead/toolbox/homepage.htm>.
- Herrero, M., P. Thornton, A. Notenbaert, S. Wood, S. Msangi, H. Freeman, D. Bossio, J. Dixon, M. Peters, and J. Van de Steeg. 2010. "Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems." *Science* 327(5967):822.
- International Fund for Agricultural Development. 1998. "Agricultural Implements Used by Women Farmers in Africa." Rome.
- Jacoby, H. 1993. "Shadow Wages and Peasant Family Labour Supply: An Econometric Application to the Peruvian Sierra." *The Review of Economic Studies* 60(4): 903–921.
- Keftasa, D. 1988. "Role of Crop Residues as Livestock Feed in Ethiopian Highlands." In B. H. Dzowela, ed. *African Forage Germplasm and Extensive Livestock Production Systems*. Nairobi, Kenya: International Livestock Research Institute.
- Kelley, T., P. Rao, and T. Walker. 1993. "The Relative Value of Cereal Straw Fodder in the Semiarid Tropics of India: Implications for Cereal Breeding Programmes at ICRISAT." In K. Diviral, ed. *Research for Agricultural Technology Development: Spatial and Temporal Dimensions*. Wallingford, UK: CAB International, pp. 88–105.
- Krinsky, I., and A. Robb. 1986. "On Approximating the Statistical Properties of Elasticities." *The Review of Economics and Statistics* 68(4):715–719.
- Le, K. 2009. "Shadow Wages and Shadow Income in Farmers' Labor Supply Functions." *American Journal of Agricultural Economics* 91(3):685–696.
- Lesorogol, C. 2010. "Creating Common Grazing Rights on Private Parcels: How New Rules Produce Incentives for Cooperative Land Management." In R. Marshall, ed. *Cooperation in Economy and Society*. Lanham, MD: Altamira Press, pp. 239–258.
- Lowe, E. 1997. "Creating by-Product Resource Exchanges: Strategies for Eco-Industrial Parks." *Journal of Cleaner Production* 5 (1–2):57–65.
- Magnan, N., T.J. Lybbert, R. Mrabet, and A. Fadlaoui. 2011. "The Quasi-Option Value of Delayed Input Use under Catastrophic Drought Risk: The Case of No-Till in Morocco." *American Journal of Agricultural Economics* 93(2):498–504.
- McDowell, R. and P. Hildebrand. 1980. "Integrated Crop and Animal Production." New York: The Rockefeller Foundation.
- Mrabet, R. 2008. *No-Tillage Systems for Sustainable Dryland Agriculture in Morocco*. Rabat: Institut National de la Recherche Agricole.
- . 2002. "Wheat Yield and Water Use Efficiency under Contrasting Residue and Tillage Management Systems in a Semiarid Area of Morocco." *Experimental Agriculture* 38(2):237–248.
- Nordblom, T., and F. Shomo. 1993. "Livestock and Feed Trends in West Asia and North Africa: Past, Present and Future." *Cahiers Options Méditerranéennes* 1(5):15–30.
- Pieri, C., G. Evers, J. Landers, P. O'Connell, and E. Terry. 2002. "No-Till Farming for Sustainable Rural Development." Washington, DC: International Bank for Reconstruction and Development.
- Rao, P., and A.J. Hall. 2003. "Importance of Crop Residues in Crop-Livestock Systems in India and Farmers' Perceptions of Fodder Quality in Coarse Cereals." *Field Crops Research* 84(1–2):189–198.
- Renard, C. 1997. *Crop Residues in Sustainable Mixed Crop/Livestock Farming Systems*. Wallingford, UK: CAB International.
- Séré, C., and H. Steinfeld. 1996. "World Livestock Production Systems: Current Status, Issues, and Trends." Rome: Food and Agriculture Organization.
- Singh, I., L. Squire, and J. Strauss. 1986. "The Basic Model: Theory, Empirical Results, and Policy Conclusions." In I. Singh,

- L. Squire, and J. Strauss, ed. *Agricultural Household Models, Extensions, Applications and Policy*. Baltimore and Washington, DC: Johns Hopkins University Press and The World Bank, pp. 17–47.
- Skoufias, E. 1994. “Using Shadow Wages to Estimate Labor Supply of Agricultural Households.” *American Journal of Agricultural Economics* 76(2):215.
- Smil, V. 1999. “Crop Residues: Agriculture’s Largest Harvest.” *BioScience* 49(4): 299–308.
- Sonoda, T., and Y. Maruyama. 1999. “Effects of the Internal Wage on Output Supply: A Structural Estimation for Japanese Rice Farmers.” *American Journal of Agricultural Economics* 81(1):131–143.
- Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, and C. de Haan. 2006. *Livestock’s Long Shadow: Environmental Issues and Options*. Rome: Food and Agriculture Organization.
- Tarhzouti, O., B. Boulanouar, and M. Silbaoueih. 2006. “L’élevage Ovin En Bour Defavorable: Caracteristiques, Atouts Et Contraints.” In B. Boulanouar, and R. Paquay, ed. *L’élevage Du Mouton Et Des Systèmes De Production Au Maroc*. Rabat: Institut National de la Recherche Agronomique, pp. 159–175.
- Teece, D. 1982. “Towards an Economic Theory of the Multiproduct Firm.” *Journal of Economic Behavior & Organization* 3(1):39–63.
- Thomas, D., J. Finlayson, A. Moore, and M. Robertson. 2010. “Profitability of Grazing Crop Stubbles May Be Overestimated by Using the Metabolisable Energy Intake from the Stubble.” *Animal Production Science* 50(7):699–704.
- Thornton, P.K., and M. Herrero. 2010. “Potential for Reduced Methane and Carbon Dioxide Emissions from Livestock and Pasture Management in the Tropics.” *Proceedings of the National Academy of Sciences* 107(46):19667–19672.
- Traxler, G., and D. Byerlee. 1993. “A Joint-Product Analysis of the Adoption of Modern Cereal Varieties in Developing Countries.” *American Journal of Agricultural Economics* 75(4): 981–989.