Property rights enforcement and no-till adoption in crop-livestock systems

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Abstract
In developing country agriculture property rights over crop residue left on privately farmed land are often poorly enforced, resulting in common grazing. The introduction of no-till agriculture, a technology that presents an alternative use for residue, may sufficiently increase its value so that farmers enforce property rights over this resource. Enforcement by no-till adopters diminishes the amount of common residue available for grazing, and consequently makes the adoption of no-till by other farmers more costly. Using a model of property rights enforcement and technology adoption in a mixed crop-livestock system calibrated with data from Morocco, I demonstrate how one farmer’s no-till adoption can prevent other farmers from adopting.

Keywords: Crop-livestock farming, No-till, Property rights, Residue, Stubble

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1. **Introduction**

Mixed crop-livestock farming systems are highly prevalent worldwide, particularly in developing countries.¹ These systems contain nearly 70 percent of the world’s ruminant population and account for close to 50 percent of the world’s cereals, 75 percent of the world’s milk, and 60 percent of the world’s meat (Herrero, et al., 2010, Steinfeld, et al., 2006). Because agricultural byproduct trade is costly, crop-livestock farmers leverage complementarities of production by 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 residue can be divided into straw, which can be transported and marketed, and stubble, which remains on the field and is rarely, if ever, traded. In many instances, farmers cannot or do not exert property rights over their crop stubble, which creates a system of mixed property rights where farmers privately farm their land, but stubble becomes a common property resource for grazing. In some cases, crop stubble is a tightly managed resource held by a distinct group of individuals (Godoy, 1991, Hoffmann, 2004, Powell, et al., 2004, Smith, 2000, Wade, 1987). In other cases crop stubble is an unmanaged common resource over which access can be denied, but intensity of use is unregulated (Ekboir, 2002, Lesorogol, 2010).²

While crop stubble has value as livestock feed, the benefit of private grazing may be less than the cost of enforcement, particularly when stubble is abundant. If the resource is scarce its value is higher and the benefits of enforcing property rights may exceed the costs. Enforcement may also become beneficial upon the introduction of an agricultural technology that offers a new and more valuable use for the

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¹ A common definition of a crop-livestock system is one in which more than 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 (FAO 1996).

² Bromley (1991) and Feeny et al. (1990) help elucidate the differences between the terms “common property” and “open access”. In this paper I refer to crop stubble as common property; use is limited to farmers in a given community, but intensity of use is unregulated. I assume that if a farmer decides to enforce property rights and exclude others from grazing his land, he can continue to graze his livestock on other farmers’ land, provided the other farmers do not also enforce property rights (at a private cost to themselves).
resource. If some farmers enforce property rights in order to adopt this technology, the pool of common stubble decreases, which would make adoption by subsequent farmers more costly.

The paper proceeds as follows. In Section 2 I provide some background on no-till agriculture (NT), the shadow price of crop stubble, and the relationship between property rights enforcement and technology adoption. In Section 3 I present a multi-household model of cereal-livestock farmers who interact in a mixed property rights regime where farming is done privately and crop stubble is commonly grazed after harvest. I demonstrate how households that do not initially enforce property rights for grazing may do so upon the introduction of a new technology that increases the value of the common resource, and how their property rights enforcement increases the cost of NT adoption for subsequent farmers. In Section 4 I calibrate the model using household and agronomic data from the Middle Atlas region of Morocco and present simulation results. In Section 5 I discuss some extensions to the model, and in Section 6 I conclude.

2. **Shadow prices, technology adoption, and property rights enforcement**

In his seminal paper on property rights, Demsetz (1967) states that, “Changes in knowledge result in changes in production functions, market values, and aspirations. New techniques, new ways of doing the same things, and doing new things all invoke harmful and beneficial effects to which society has not been accustomed. It is my thesis…that the emergence of new property rights takes place in response to the desires of interacting persons for adjustment to new benefit-cost possibilities” (p. 350). NT could be such technique; by presenting a new use for crop stubble, NT changes the benefit-cost calculus crop-livestock farmers face as they decide whether or not to enforce property rights.

Crop stubble is a nonmarket good and has no market price. However, stubble does have a shadow (or implicit) price that can be affected by the introduction of a new technology such as NT. NT is

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3 Lesorogol (2008) reports instances of farmers attempting to sell grazing rights to stubble that were met with strong opposition from other farmers. This author noted rare instances of farmers selling, or trying to sell, stubble grazing rights in Morocco. These attempts were also at times met with fervent resistance from other community members.
generally thought to produce yields at least as great as those achieved through conventional tillage methods (CT), but with increased sustainability over time; less sensitivity to rainfall variation; and lower requirements for labor, fuel, and seeds (Ekboir, 2002, Erenstein, 2003, Lal, 2007, Mrabet, 2008, Pieri, et al., 2002). NT requires that the farmer maintain a layer of permanent vegetative matter composed of crop stubble from previous years. Farmers therefore face a tradeoff between using residue for livestock production, for which it has one shadow price, or as input for crop production, for which it has a different shadow price. If the shadow price of stubble as feed is lower than the cost of enforcement, and the shadow price of stubble as an input for NT is higher than the cost of enforcement, the introduction of NT will result property rights enforcement over a resource previously used in common.

Enforcement of property rights by any one farmer reduces the total amount of stubble available for common grazing; therefore each farmer’s enforcement increases all other farmers’ shadow prices for stubble as feed. Interdependence of property rights enforcement and technology decisions can therefore arise across farmers. DeMeza and Gould (1992) elaborate the concept of interdependence of property rights enforcement using a theoretical model of multiple landowners engaging common grazing of private land because of prohibitively high enforcement costs. When a less labor-intensive technology—wheat farming—is introduced, some landowners enforce property rights in order to cultivate land previously used as common pasture. Because landowners interact in a labor market, each one that adopts wheat cultivation causes the price of labor for all to drop, which increases the benefit of private grazing compared to wheat cultivation or leaving the land as common pasture. A cascade of privatization ensues, and in the end all the land is either used for private grazing or wheat cultivation; no land is left for common grazing.

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4 In addition to improving farmer revenue, no-till offers global environmental benefits: lower emissions from agricultural machinery and farmland that acts as a carbon sink. As climate change becomes a more important issue worldwide, the mitigating benefits of no-till are gaining more attention among policymakers (see World Bank 2010).

5 In their model DeMeza and Gould (1992) do not allow for the possibility of land being privately cultivated during the growing season and commonly grazed afterward.
Interdependence of technology adoption becomes a greater concern when households are heterogeneous. Agricultural extension is resource constrained, so there are many reasons why agents might disseminate new technologies first to larger, wealthier, more educated, and better connected farmers with the hope that these technologies will spill over to smaller and more isolated farmers (Anderson and Feder, 2004). Farmers with relatively large amounts of land stand to benefit from more from experimentation, and empirically have been shown to be first adopters (Besley and Case, 1994, Feder, 1980). The literature on social learning in agriculture indicates that technology adoption by one farmer encourages subsequent adoption (Bandiera and Rasul, 2006, Foster and Rosenzweig, 1995, Maertens, 2013, Magnan, et al., 2013, McNiven and Gilligan, 2012, Munshi, 2004). However, there could be a negative effect of early adoption for a technology that has the potential to increase property rights enforcement and change relative (shadow) prices. In a common or mixed property rights regime, the uptake of technologies that require adopters to enforce property rights over resources previously held in common could make adoption by other farmers costlier.

3. Multi-household cereal-livestock farming model

I use a constrained optimization problem to demonstrate the formation of a farmer’s individual shadow price of crop stubble. The model begins with \( N \) cereal-livestock farmers. Farmer \( i \) has landholdings of area \( L^i \) and a herd of size \( H^i \), which are both exogenous.\(^6\) In Section 5 I address the possible implications of allowing for endogenous herd size in the model. Farmer \( i \) maintains his herd by feeding it a combination of crop stubble, \( B^i \), and a bundle of complimentary market feed (straw, hay, bran, maize, beet pulp, etc.) of total value \( M^i \). I define livestock production (or maintenance) as a function of stubble and market feed, \( g(B^i; M^i) \), which is continuous, increasing, and concave in both arguments. Complimentary feed is either produced on-farm or acquired at market at an exogenous price. I ignore

\(^6\) Exogenous herd size may be a plausible assumption in the short term, but farmers can adjust their herd size over time for various reasons. However, the degree to which small farmers can adjust their herds is limited by indivisibilities and returns to scale in herding, and farmers may not be willing to draw down their herds to experiment with a new technology. It is reasonable to think farmers would treat their herd size as fixed when contemplating a new technology, and for simplicity I maintain the assumption of exogenous and constant herd size.
transaction costs for market feed so that a farmer who uses feed produced on-farm incurs an opportunity cost equal to the market price. I will address how transport costs and other market imperfections could impact the model in Section 5.

The farmers in the model use all of their land to grow wheat. Before the introduction of NT, farmers have two possible uses for land covered in stubble during the non-growing season: allow common stubble grazing, or enforce property rights at a private cost and graze stubble exclusively. When NT is introduced, farmers have a third option, which is to enforce property rights and leave stubble on the field as an input to NT. In the model, $Q_{EX}$ indicates the amount of land farmer $i$ dedicates to private grazing and $Q_{NT}$ indicates the amount he allocates to NT. Stubble is produced proportionately with cereal so that the total quantity of stubble available on farmer $i$’s land is $\gamma \cdot L^i$, which can be normalized to $L^i$. Each farmer’s herd grazes a quantity of common stubble proportionate to the size of his herd relative to the aggregate herd. On privately grazed land, the farmer’s herd grazes all of the stubble, and on NT land the farmer’s herd grazes nothing.\footnote{In many cases, limited grazing on NT plots does not affect crop performance. A somewhat arbitrary rule of thumb is that 70 percent of stubble can be removed. However, in drier climates this number is much lower. Mrabet (2002) finds that in semiarid Morocco up to 30 percent of stubble can be removed or grazed without sacrificing yield. For the purposes of the model, I assume that all stubble must be left on the ground for successful NT.}

3.1 Enforcement of property rights for private grazing

First, I examine farmer $i$’s decision of how much land to privately graze, without the option of NT. To decide how much land to use for private grazing, farmer $i$ minimizes the cost of market feed needed to maintain his herd of size $H^i$ plus enforcement costs $E$. The amount of stubble consumed by farmer $i$’s herd if no farmers enforce property rights is $B^i = \frac{H^i}{\sum_j H^j} \cdot \sum_j L^j$, where $j$ indexes all farmers. Farmer $i$ chooses an area of $Q_{EX}^i$ between 0 and $L^i$ to privately graze, increasing his access to stubble to $B^i = \frac{H^i}{\sum_j H^j} \cdot \left( \sum_j L^j - Q_{EX}^i \right) + Q_{EX}^i$, where $\frac{H^i}{\sum_j H^j} \cdot \left( \sum_j L^j - Q_{EX}^i \right)$ is the quantity of common stubble grazed by farmer $i$.
and $Q^i_{EX}$ is the amount of private stubble. I ignore any fixed costs of property rights enforcement. Farmer

$i$’s constrained minimization problem is:

$$g(B^i, M^i) \geq H^i \text{ (feed constraint)}$$

$$\min_{B^i, M^i, Q^i_{EX}} M^i + E \cdot Q^i_{EX} \text{ subject to } B^i \leq \frac{H^i}{\sum_j H^j} \cdot \left( \sum_j L^j - Q^i_{EX} \right) + Q^i_{EX} \text{ (stubble constraint)}$$

$$0 \leq Q^i_{EX} \leq L^i \text{ (land and non-negativity constraint)}$$

The associated Lagrangian is:

$$\mathcal{L}^i = M^i + E \cdot Q^i_{EX} + \lambda^i \cdot \left( H^i - g(B^i, M^i) \right)$$

$$+ \rho^i \cdot \left( B^i - \frac{H^i}{\sum_j H^j} \cdot \left( \sum_j L^j - Q^i_{EX} \right) - Q^i_{EX} \right) - \mu^i \cdot Q^i_{EX} + \sigma^i \cdot \left( Q^i_{EX} - L^i \right).$$

I differentiate [1] with respect to $B^i$ and $M^i$ to solve for $\rho^i$, the shadow price of stubble:

$$\rho^i = \frac{\frac{\partial g(B^i, M^i)}{\partial B^i}}{\frac{\partial g(B^i, M^i)}{\partial M^i}} \quad [2]$$

Note that $\rho^i$ is decreasing in $B^i$. The first order condition of [1] with respect to $Q^i_{EX}$ is:

$$\rho^i = \frac{E + \sigma^i - \mu^i}{1 - \frac{H^i}{\sum_j H^j}} = E + \sigma^i - \bar{\rho}^i \quad [3]$$

In [3], $\mu^i$ is the Lagrangian multiplier associated with the constraint that $Q^i_{EX}$ cannot be negative and $\sigma^i$ is the lagrangian multiplier associated with the constraint that $Q^i_{EX}$ cannot exceed $L^i$. When the constraints are not binding, the multipliers equal zero, otherwise they are positive. Therefore $\bar{\rho}^i > 0$ if the farmer exclusively grazes none of his land and $\bar{\sigma}^i > 0$ if the farmer exclusively grazes all his land.
To minimize costs, farmer \( i \) adjusts \( Q^i_{EX} \) and \( M^i \) so that his shadow price of stubble equals the cost of exclusive grazing, adjusted for the size of his herd relative to the aggregate herd. If the farmer has a relatively small stubble endowment relative to his grazing needs, and consequently his shadow price of stubble is higher than the adjusted cost of enforcement, then he will increase the amount of land on which he exclusively grazes until either \( \rho^i(B^i) = E \) or \( Q^i_{EX} = L^i \). However, if the farmer has a large enough initial endowment of stubble that the shadow price of stubble is less than the adjusted enforcement cost, i.e., \( \rho^i(B^i) < E \), the farmer will set \( Q^i_{EX} = 0 \). This situation is the status quo in the mixed property rights regime.

### 3.2 Enforcement of property rights for exclusive grazing or no-till adoption

Upon the introduction of NT, farmers can either enforce property rights over stubble for private grazing, or as an input for crop production. I assume yields under NT and conventional tillage CT are the same, but that the cost of production are lower under NT than CT, even after accounting for the cost of enforcing property rights over stubble. The amount of stubble available to the farmer, \( B^i \), is now a function of how much land he dedicates to private grazing, how much land he dedicates to NT, the aggregate amount of cereal land available for grazing, and his herd size compared to the aggregate herd:

\[
B^i = \frac{H^i}{\sum_j H^j} \cdot \left( \sum_j L^j - Q^j_{EX} - Q^j_{NT} \right) + Q^i_{EX}.
\]

The farmer’s optimization problem is therefore:

\[
\min_{B^i, M^i, Q^i_{EX}, Q^i_{NT}} M^i + E \cdot Q^i_{EX} + C_{CT} \cdot (L^i - Q^i_{NT}) + (C_{NT} + E) \cdot Q^i_{NT}
\]

subject to

\[
\begin{align*}
\min_{B^i, M^i, Q^i_{EX}, Q^i_{NT}} & & M^i + E \cdot Q^i_{EX} + C_{CT} \cdot (L^i - Q^i_{NT}) + (C_{NT} + E) \cdot Q^i_{NT} \\
& & g(B^i, M^i) \geq H^i \quad \text{(feed constraint)} \\
& & B^i \leq \frac{H^i}{\sum_j H^j} \cdot \left( \sum_j L^j - Q^j_{EX} - Q^j_{NT} \right) + Q^i_{EX} \quad \text{(stubble constraint)} \quad [4] \\
& & Q^i_{EX}, Q^i_{NT} \geq 0 \quad \text{(non-negativity constraints)} \\
& & Q^i_{EX} + Q^i_{NT} \leq L^i \quad \text{(land constraint)}
\end{align*}
\]
The shadow price of stubble, \( \rho^i \), as a function of \( B^i \) and \( M^i \) is the same as in [2] and, and [3] must still hold. Solving [4] with respect to \( Q^i_{NT} \) yields:

\[
\rho^i = \frac{C_T - C_{NT} - E + \varphi^i - \sigma^i}{\sum_j H^j} = \zeta + \varphi^i - \sigma^i,
\]

where \( \varphi \) is the Lagrangian multiplier associated with the non-negativity constraint for \( Q^i_{NT} \). In [5], \( \varphi^i > 0 \) if the farmer puts no land into NT and \( \sigma^i > 0 \) if the farmer enforces property rights on all of his land, either for NT, exclusive grazing, or a combination thereof. To minimize costs, farmer \( i \) will adjust \( Q^i_{NT} \) and \( Q^i_{NT} \) so that [3] and [5] both hold. How he does this depends on the relative costs of enforcing property rights for private grazing compared to the cost savings of using NT and his initial stubble endowment.

Suppose the adjusted cost of property rights enforcement is less than the adjusted cost savings from NT adoption, i.e., \( E < \zeta \). In this “low enforcement costs” scenario, for [3] and [5] to both hold it must be true that \( \sigma^i > 0 \). This means that all land is either used for exclusive grazing or is put under NT; none of farmer \( i \)’s land will be left for common grazing. If farmer \( i \)’s initial shadow price of stubble is greater than the adjusted cost savings of NT, i.e., \( \rho^i(B^i_0) > \zeta > E \), farmer \( i \) will enforce property rights for exclusive grazing until either all land is used for private grazing, or until the shadow price of stubble is lower than the cost savings from NT, at which point the farmer will use some land for private grazing and the rest of the land for NT. If \( \rho^i(B^i_0) < E < \zeta \) the farmer will put land into NT until either all land is under NT or until the shadow price of stubble is higher than the cost of property rights enforcement for private grazing, at which point the farmer will keep some land under NT and use the rest of the land for private grazing. If \( E < \rho^i(B^i_0) < \zeta \) farmer \( i \) will also exclusively graze some land and put the rest of this land into NT.

Now suppose that the adjusted cost of property rights enforcement for private grazing is greater than the adjusted cost savings from NT adoption, i.e., \( E > \zeta \). In this “high enforcement costs” scenario,
for [3] and [5] to both hold it must be true that either $\bar{\mu}^i > 0$ (farmer $i$ exclusively grazes no land), $\bar{\varphi}^i > 0$ (farmer $i$ puts no land in NT), or both. He will never engage in both private grazing and NT, and may leave some land to communal grazing. If farmer $i$’s initial shadow price of stubble is greater than the adjusted cost of exclusive grazing, i.e., $\rho^i(B^i_0) > \bar{E} > \bar{C}$, he will privately graze at least some of his land and put no land in NT. If his initial shadow price of stubble is less than the adjusted cost savings from NT, i.e., $\bar{E} > \bar{C} > \rho^i(B^i_0)$, he will put land into NT and not exclusively graze any land. If $\bar{E} > \rho^i(B^i_0) > \bar{C}$, then the farmer will not enforce property rights for private grazing and nor will he put land into NT. This situation is akin to a price band (De Janvry, et al., 1991), where the farmer will neither “buy” stubble by enforcing property rights for private grazing, nor “sell” stubble by diverting it to crop production by using NT.

3.3 Interdependence of property rights enforcement and technology adoption

Until this point I have considered a single farmer’s optimization problem without taking into account other farmers’ property rights enforcement. However, because each farmer’s shadow price of stubble depends on the amount of stubble available to them, and the amount available to them depends on other farmers’ enforcement, farmers’ decisions regarding property rights enforcement and NT adoption are interdependent.

When property rights enforcement by other farmers is taken into account, the amount of stubble available to farmer $i$ is $B^i = \frac{H^i}{\sum_i H^i} \cdot \left( \sum_j L^j - Q^{\bar{E}}_{ENF} - Q^i_{EX} - Q^i_{NT} \right) + \gamma \cdot Q^i_{EX}$, where $Q^{\bar{E}}_{ENF} = \sum_{j \neq i} Q^j_{EX} + \sum_{j \neq i} Q^j_{NT}$. To farmer $i$ it does not matter if other farmers enforce property rights for private grazing or for NT; it only matters over how much land they enforce property rights. The quantity of stubble farmer $i$ gains access to by enforcing property rights for private grazing, or the amount he loses access to by adopting NT, is not affected by $Q^{\bar{E}}_{ENF}$, i.e., $\frac{\partial B^i}{\partial Q^i_{EX}}$ and $\frac{\partial B^i}{\partial Q^i_{NT}}$ are not functions of $Q^{\bar{E}}_{ENF}$. However, because farmer $i$’s shadow price of stubble depends on the total amount available to him, which depends on all
farmers’ property rights enforcement, the value of the stubble farmer $i$ gains access to by enforcing property rights for private grazing, or the amount he loses access to by adopting NT, is affected by $Q^i_{ENF}$; $\frac{\partial \rho^i}{\partial Q^i_{kx}}$ is negative and decreasing in $Q^i_{ENF}$ and $\frac{\partial \rho^i}{\partial Q^i_{NT}}$ is positive and increasing in $Q^i_{ENF}$. Therefore as other farmers increase property rights over their crop residue, farmer $i$ will engage in more private grazing and put less land in NT.

4. **Simulation**

In this section I present a simulation model calibrated with data from the Meknès region of Morocco to demonstrate the relationship between the shadow price of stubble, property rights enforcement, and NT adoption across farmers. The Meknès region is a major rainfed cereal growing where nearly all farmers also own livestock that they feed a mix of crop residue and various market feeds. Agronomic field trials conducted by the National Agricultural Research Institute of Morocco (INRA) have shown NT to be successful in and around the region, resulting in yields at least as great as those achieved by CT at lower costs (Mrabet, 2008, Mrabet, 2002, Mrabet, 2010). However, uptake by farmers is virtually non-existent in the Meknès region and scarce in the nearby Settat region, where approximately 80 farmers were using no-till on a trial basis with technical assistance from INRA in 2009, with generally positive results (Personal communication with Azzedine El Brahli, June 2009). In group interviews, farmers reported interest in no-till, but hesitation over adopting the technology because of the importance of crop stubble as animal feed.

I solve the model using a mixed-integer solver in the General Algebraic Modeling System (GAMS). To align with the theoretical model I present in Section 3, I show model results with and without the possibility of NT adoption. I also present results using high and low costs of property rights enforcement. Finally, I show how fixed costs to NT adoption accentuate interdependencies of adoption.

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8 The mixed-integer solver is only necessary when fixed costs of NT are incorporated in the model. Otherwise a continuous solver can be used.
4.1 Model parameterization

To calibrate the model I use survey data on cereal area farmed \((L)\), herd size \((H)\), consumption of crop stubble \((B)\) and other feeds, and the market price of traded feeds. Consumption of tradable feed sources is straightforward to measure. Consumption data for is more difficult to obtain from farmers. Farmers do not generally know the area of crop stubble their herd grazed, but they do know how for approximately how many days they grazed their herds on stubble. For this reason I use the livestock weighted grazing day \((\text{LWD})\) as the unit of stubble consumed, which is calculated as the number of Tropical Livestock Units \((\text{TLU})\) times days of grazing.\(^9\)

For the simulation I put two representative crop-livestock farming households into a mixed property rights regime as previously described.\(^10\) The “small” farmer is representative of those in the first quartile of landholdings; he has 2 ha of land and a herd of size 3.7 TLU. The “large” farmer is representative of those in the fourth quartile of landholdings; he has 8 ha of land and a herd size of 5.9 TLU. I assume that there are 1.25 ha of common grazing land upon which property rights are never enforced in order to keep \(B_{\text{small}}\) from approaching zero; this could be stubble from other farmers’ fields or from uncultivated grasslands substitutable for stubble. Based on data on stubble grazing, I assume that each hectare of stubble can support 156 days of grazing by one TLU.

To calculate cost savings from using NT over CT I use prescribed input dosages and prices provided by INRA and described in greater detail in Magnan et al. (2011). These data cover all machinery hire, pesticides, manual weeding labor, harvesting, and hay baling. The main cost differences between the two technologies are plowing, which is only done for CT, seed dosage, which can be one-third lower under NT, and herbicide use, which is more intensive under NT. CT is estimated to cost 3515 Dh per hectare and NT is estimated to cost 2905 Dh per hectare, excluding enforcement costs.

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\(^9\) This is the common conversion rate employed by the FAO (http://www.fao.org/docrep/V1650T/v1650T0d.htm). One sheep or goat counts as 0.1 TLU and one cow or equine counts as 0.7 TLU.

\(^10\) These “large” farming households, and most of the larger farming households captured by the survey, are considered small farmers by Moroccan standards.
I run the simulation under two scenarios. I first assume low enforcement costs of 200 Dh per acre, then I assume high enforcement costs of 500 per acre. I assume that there are no fixed costs to enforcing property rights, and initially that there are no fixed costs to NT adoption. I parameterize the livestock maintenance function using estimates from Magnan et al. (2012). These authors estimate the function $H^i = g(B^i, M^i)$ in [1], assuming a Cobb-Douglas functional form and constant returns to scale. From the function $H^i = AB^i M^i$, the parameter estimates $\alpha_B$ and $\alpha_M$ can be used to calculate the shadow price of stubble as $\rho^i = \frac{\alpha_B}{\alpha_M} \frac{M^i}{B^i}$, where $P_M$ is the price of the market feed.\footnote{Specifically, I assume that straw is the market feed and use estimates of $\alpha$ for straw, stubble, and complementary from Magnan et al. (2012) to parameterize the livestock maintenance function.} A summary of model parameters can be found in Table 1.

4.2 Simulation results

Initially, I consider the case where NT is not an option and all property rights enforcement is done for private grazing. I solve the small farmer’s constrained cost minimization problems over various property rights enforcement decisions of the large farmer ranging from no enforcement to enforcement over his entire 8 ha. When enforcement costs are low, the small farmer will not enforce property rights on any of his land if the large farmer enforces property rights on less than 3 ha. Beyond 3 ha, as the large farmer increases the amount of land upon which he enforces property rights, so does the small farmer. If the large farmer enforces property rights on 6 ha or more, the small farmer enforces property rights on all of his land (Figure 1, top left). When enforcement costs are high, the small farmer does not enforce property rights on his land unless large farmer enforces property rights on at least 4.7 ha of his land. If the large farmer enforces property rights on all of his land, so does the small farmer (Figure 1, top right).

Next I consider the case where NT is an option. Under both low and high enforcement costs, the small farmer will practice NT on all of his land if the large farmer does not enforce any property rights. As in the theoretical model, it does not matter to the small farmer whether the large farmer enforces...
property rights for exclusive grazing or NT. When enforcement costs are low, if the amount of land upon which the large farmer enforces property rights surpasses 2.2 ha, the small farmer will begin to convert land from NT to private grazing. If the large farmer enforces property rights on more than 7.3 ha of his land the small farmer will graze all of his own land privately, and leave none in NT (Figure 1, bottom left).

When enforcement costs are high, the small farmer behaves slightly differently. If the large farmer does not enforce property rights on any of his land, the small farmer will put all of his land under NT. If the large farmer enforces property rights over at least 0.7 ha, the small farmer will convert land from NT to common grazing land. If the large farmer increases his property rights enforcement to 2.7 ha, will not use any land for NT or private grazing. If the large farmer further increases his property rights enforcement to 4.7 ha, the small farmer will begin to enforce property rights on his own land for exclusive grazing. When the large farmer enforces property rights on all of his land, the small farmer will also enforce property rights on all of his land, entirely for exclusive grazing (Figure 1, bottom right).

In addition to the small farmer’s land allocations as a function of the large farmer’s property rights enforcement, Figure 1 shows the small farmer’s shadow price of stubble as a function of the large farmer’s enforcement. This illustrates the theoretical findings in Section 3 that connect the farmer’s land use decisions to his shadow price of stubble. The small farmer’s shadow price of stubble is lowest when all stubble is available for common grazing. As the large farmer enforces property rights over more of his land, the small farmer’s shadow price increases. Once the small farmer’s shadow price of stubble surpasses the adjusted cost of property rights enforcement, he can keep the shadow price constant by enforcing property rights for private grazing, either at the expense of land left to common grazing or land put into NT. Once the small farmer has enforced property rights for private grazing on all of his land, his shadow price of stubble again begins to increase.
Farmers may face substantial fixed costs of NT adoption. These costs could include the acquisition of skills and search and transaction costs for machinery and complimentary inputs such as pesticide. Fixed costs would pose an especially high barrier to adoption by small farmers, who have less land to spread these costs over. Figure 2 contains results of simulations where the small farmer faces a fixed cost of 100 Dh for NT adoption. When enforcement costs are low, fixed costs make very little difference; a farmer will put all of this land in NT unless the large farmer enforces property rights over at least 2.2 ha, and he will put at least some of his land in NT unless the large farmer enforces property rights over at least 6 ha of his land. When enforcement costs are high fixed costs have a more pronounced effect on NT adoption. The small farmer will adopt NT on all of his land if the large farmer does not enforce property rights on any of his land, but will not engage in any NT if the large farmer enforces property rights over as little as 0.2 ha.

5. **Discussion and extensions**

The model and simulation I present in this paper depend on some reasonable, yet restrictive assumptions. In this section I discuss some of these assumptions in more detail, and conceptually demonstrate that the main results of this paper hold without them.

Throughout the paper I assume herd size is constant. A possible extension to the model would be to allow for endogenous herd size. The extent to which a farmer adjusts his herd will depend on the role of livestock to his household (productive asset, savings, insurance, status, etc.), livestock transaction costs, and herd dynamics. If herd size is endogenous, the farmer would have another margin on which to minimize total costs. Consequently, farmers would be able to sell livestock in order to continue using NT when the quantity of common stubble diminishes, or to avoid having to enforce property rights for common grazing. The effect of the large farmer’s property rights enforcement on the small farmer’s property rights enforcement and NT adoption would be less pronounced, but still evident and of the same direction.
The model results I present depend on the assumption of imperfect substitutability between crop stubble and market feed, i.e., that substitution between feed sources cannot be made at constant rates, irrespective of the animals’ diet. If I assume a linear livestock production, i.e., one that imposes perfect substitutability of feed sources, the shadow price of stubble would be constant absent market failures. While the assumption of imperfect substitutability is highly plausible, the results of this paper also hold with a linear livestock maintenance function if transaction costs or liquidity constraints exist.

If there are transaction costs for trading straw— a potential substitute for stubble— the effective price of straw will be lower (higher) than the market price for net sellers (buyers). Farmers that place a lower value on straw than the buying price but a higher value than the selling price will not engage in straw markets, and consequently their shadow price of stubble will adjust to reflect the amount of stubble available to them. As shown in the theoretical model, when the shadow price of stubble depends on the amount of stubble left by others for common grazing, interdependencies arise.

The effective price a farmer pays for a market feed may also differ from the market price because of liquidity constraints. A farmer that has the cash required to purchase the optimal amount of market feed while not sacrificing consumption elsewhere (health, education, entrepreneurial activities, etc.) pays the actual market price for feed (plus transaction costs). A farmer that is liquidity constrained will need to either borrow, purchase less than the optimal quantity, or reduce consumption elsewhere, which imposes additional costs on the household. The effective price of market feed to a liquidity-constrained farmer is therefore increasing in the amount purchased. Consequently, the shadow price of stubble will also be affected by the property rights enforcement decisions of others, even if the livestock maintenance function is linear.

6. **Concluding remarks**

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12 There are obvious nutritional complementarities between hay, grain, and other concentrated feed sources and crop residue. There are also likely differences between straw, which contains no grain, and stubble, which often contains grains knocked to the ground during harvest (personal communication with Abdelaziz Chergauoi, August 2007, Thomas et al. 2010).
The introduction of a new technology can present new uses and higher values for factors of production, which can incite individuals to enforce property rights over resources previously held in common. Where cereal production is done on private land but property rights over stubble are not fully enforced, the introduction of NT could increase the value of stubble sufficiently to some farmers so that they enforce property rights over it. For farmers who share common stubble grazing land with an adopting farmer, a decrease in the aggregate amount of the common resource available will increase their own valuation of crop stubble, which in turn poses a greater barrier to NT adoption and increases the benefit of private grazing. I demonstrate this interdependence of property rights enforcement and technology adoption with a simulation model calibrated with data from Morocco. The simulation shows that interdependencies are particularly strong when there are fixed costs of technology adoption.

More generally, technologies that require users to reduce provision of a common resource still merit special consideration because poorer households are often more dependent on common resources, and would stand to suffer the most from increased property rights enforcement (Cavendish, 2000, Jodha, 1992).13 While NT is often thought of as a pro-poor technology, adoption by larger farmers may actually have a negative welfare impact on those thought to benefit the most from the technology if crop stubble is a common resource. Site-specific investigation of property rights regimes governing stubble use would be prudent before attempts to disseminate NT so that appropriate compensation measures could be put into place, i.e., improved access to market feed for poor households.

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13 Some studies find evidence contrary to this common assertion (Adhikari 2005; Narain et al. 2005).
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References


