Booming markets for Moroccan argan oil appear to benefit some rural households while threatening the endemic argan forest

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Morocco's argan oil is now the most expensive edible oil in the world. High-value argan markets have sparked a bonanza of argan activity. Nongovernmental organizations, international and domestic development agencies, and argan oil cooperatives aggressively promote the win–win aim of simultaneously benefiting local people and the health of the argan forest. This paper tests some of these win–win claims. Analysis of a panel of detailed household data suggests that the boom has enabled some rural households to increase consumption, increase their goat herds (which bodes poorly for the argan forest), and send their girls to secondary school. The boom has predictably made households vigilant guardians of fruit on the tree, but it has not incited investments in longer term tree and forest health. We evaluate landscape-level impacts of these changes using commune-level data on educational enrollment and normalized difference vegetation index data over the period from 1981 to 2009. The results of the mesoanalysis of enrollment are consistent with the microanalysis: the argan boom seems to have improved educational outcomes, especially for girls. Our normalized difference vegetation index analysis, however, suggests that booming argan prices have not improved the forest and may have even induced degradation. We conclude by exploring the dynamic interactions between argan markets, local institutions, rural household welfare, and forest conservation and sustainability.

poverty | biodiversity | nontimber forest products | normalized difference vegetation index | development economics

At $300/L or more, argan oil is currently the world's most expensive edible oil. For cosmetic uses, it demands an even higher price, and it is the subject of several US and European cosmetic patents (1). The oil, which has been a mainstay for the Berber people of southwestern Morocco for centuries, was propelled out of obscurity in the 1990s by favorable findings about its culinary, cosmetic, and even medicinal virtues. Since 1999, rapidly appreciating prices in high-value markets have sparked a bonanza of argan activity. Nongovernmental organizations, international and domestic development agencies, and argan oil cooperatives have played a central role in this bonanza, with the dual aim of alleviating rural poverty and inciting local conservation of the endemic argan tree. Both goals are worthwhile: poverty and illiteracy are relatively high in the region (2), and the argan tree, which has defied domestication (3), acts as foundation species for over 1,200 other species of plants and animals (140 endemic) in the ecoregion (4–7). Evidence of this ecological uniqueness is that the argan forest was designated as a United Nations Educational, Scientific and Cultural Organization Biosphere Reserve in 1998 (8). Win–win claims of poverty alleviation and biodiversity conservation now appear on virtually every argan product label and have been showcased by media outlets worldwide. Using a combination of household- and landscape-level analyses, we evaluate these now common argan claims.

Although the recent boom in argan prices has its roots in the unique properties of argan oil and the rarity of the endemic argan tree (*SI Discussion*), attempts to induce local biodiversity conservation through new high-value markets for nontimber forest products are now quite common. Conservation through commercialization (9) has, however, come under increasing scrutiny by researchers and policymakers in the past decade (10, 11). Conceptually, several conditions must hold before commercialization can be expected to induce conservation gains (12). Local benefits must be sufficient to induce behavioral changes. Conditional on sufficient local benefits, welfare and biodiversity impacts depend on regeneration properties (13, 14), property rights regimens within indigenous communities (10, 15, 16), sovereignty over the resource (17), and how households invest benefits that they reap (18).

Two linkages between biodiversity and poverty traps guide our analysis. First, the argan case showcases several common linkages between forest product commercialization and poverty dynamics. Because the rural poor often rely disproportionately on forest products—typically extracted through open or common access rights—they are frequently targeted by conservation through commercialization efforts. Empirical evidence of impacts on poverty and inequality has been somewhat encouraging (19–21), but in some contexts, dependence on low-return forest products by those people who have limited livelihood options may result in a poverty trap, particularly in cases where commercialization brings resource degradation (11, 22–24). Forest products often function as an important safety net by helping vulnerable households cope with hard times and thereby, may prevent households from slipping farther into poverty, but it may be difficult for such households to leverage forest products as a means of accumulating the assets needed to shift to higher-return pursuits (21). Furthermore, even the safety net benefit can be compromised if commercialization depletes forest resources, leaving vulnerable households more susceptible to adverse shocks that can drive them deeper into poverty (24).

Second, argan activities are traditionally the domain of women, suggesting that the argan boom could provide a sex-specific remedy to persistent poverty. When women benefit, outcomes for children—along with prospects for future poverty alleviation—improve (25). Specifically, higher argan product values might increases the returns to female labor, improve women's position in intrahousehold bargaining (26), and heighten their social status (27). However, an increase in returns to female unskilled labor could also increase the opportunity cost of female education, diverting girls'

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time from school to argan production and perpetuating the poverty cycle (28). In this paper, we evaluate these linkages between biodiversity and persistent rural poverty in the argan region.

Results

In this section, we first synthesize results from a recent microanalysis of the local impacts of the argan oil boom on how rural households interact with argan markets, what benefits arise from their market participation, and how their use of the forest has evolved (29). Building on this microanalysis, we present the results of mesoanalyses that test the win–win claims at a more aggregated landscape level.

Local Impacts on Rural Households and the Forest. As described in detail elsewhere (29), we use panel household data from Essaouira Province to assess the impact of the argan boom on households and their exploitation of the forest (Fig. S1). As argan prices soared between 1999 and 2007, average household argan oil production tripled, and average argan oil consumption fell by one-half. Argan fruit became a popular speculative investment,* with average household stocks increasing 10-fold. The proportion of households selling argan oil more than doubled; however, the proportion selling fruit increased more than sixfold, because the booming fruit market has turned argan fruit into an important source of income. Even more recently, markets for argan kernels began to emerge, and these markets increasingly enable locals to capture the greater value added by stripping pulp and cracking stones to extract the kernel.

We compare several measurable indicators of welfare among rural households before and after dramatic changes in argan markets. We use households' access to argan fruit in 1999 as a measure of how much they stood to benefit from the ensuing appreciation of argan prices. First, we find that households with access to more fruit enjoyed a slightly higher increase in household consumption relative to other households. Second, benefiting households accumulated more assets in the form of goats (but not other livestock); this finding bodes poorly for the forest, because goats often climb in trees to graze leaves, with negative impacts on forest health and subsequent harvests. Third, girls from households that stood to benefit from booming argan prices were significantly more likely to make the transition from primary to secondary school than girls from other households, but no such result is apparent for boys.†

The boom has also induced households to alter their exploitation of the forest. Conflicts over argan resources have increased as well as conflicts over permanent barriers around seasonal usufruct forest tracts (*SI Discussion* and Fig. S2). Although most households still graze their goats in argan trees during some periods of the year, they do so less frequently than before—and very rarely during the fruit collection season. Locals tend to harvest argan fruit more aggressively and often use sticks to dislodge fruit, which can damage branches and dislodge buds for subsequent year's production. Despite higher fruit prices, locals have shifted away from butane and to dead argan wood as a source of energy.‡ Whereas 17% of our households relied primarily on argan wood for cooking in 1999, 67% relied primarily on argan wood for cooking in 2007. With steadily increasing costs of living and stagnating income outside the argan sector, households are increasingly choosing to substitute free argan wood for purchased butane. In sum, microlevel evidence suggests that the boom is benefiting some locals, but it has altered forest exploitation by increasing short-run fruit collection incentives rather than long-run concerns of forest sustainability.

Landscape-Level Impacts. We next zoom out and assess the impact of booming argan markets on the region and forest landscape. To do this analysis, we focus our attention on aggregate welfare data at the commune level for one province and on satellite image data at the 8×8-km level for the entire region (Fig. S1). To evaluate the association between the argan boom and the response in welfare and forest changes, we follow a dose–response approach that uses booming argan prices after 1999 as the treatment and argan forest coverage as the dosage of this treatment. Using the only available panel data on welfare outcomes at the commune level, we focus our mesoanalysis of welfare impacts on education enrollment data from Essouira Province. The results (Table 1) suggest that the argan boom has had a positive impact on student enrollment in communes where educational infrastructure is weak. This effect is particularly strong for girls. Among communes with weak educational infrastructure, those communes with 65% argan forest cover saw the proportion of eligible girls enrolled increase by roughly 10% between 2000 and 2005.§

Next, we analyze satellite data to assess landscape-level trends in the density of the argan forest and forest canopy. By comparing these trends before and after the onset of the boom in 1999, we evaluate whether high-value argan commercialization has led to improvements in forest and canopy density. We quantify these density changes using the normalized difference vegetation index (NDVI) (32–36), which is used to monitor vegetation cover, plant biomass, productivity, and biodiversity in many settings (37). To validate our use of this measure, we compared NDVI with percent canopy measures based on recent satellite images taken in the argan region (*SI Discussion*). The correlation between dry season NDVI and canopy cover is high (>0.90), because trees are often the only dry season vegetation in the region. In the analysis, we control for current and cumulative rainfall to isolate anthropogenic impacts on NDVI and exploit the fact that forest floor is largely void of vegetation during the dry season to isolate the NDVI trend for the forest canopy. We display these conditional dry season NDVI trends pixel by pixel in Fig. 1. A positive (negative) conditional trend indicates a thickening (thinning) of the forest canopy net of rainfall effects.¶ Before the boom, negative trends prevailed in some portions of the southern argan forest because of dramatic expansions of irrigated agriculture in that region during the 1980s and 1990s (38, 39). Since the boom began, much of the northern argan forest appears to have thinned. Because the northern forest has attracted greater attention during the argan boom because of its proximity to major markets and popularity among tourists, this pattern seems consistent with the boom negatively affecting the forest, but we must push more to statistically test the impact of the boom.

*Argan fruit can be stored for many years without deteriorating the quality of oil extracted from the kernel. Even under ideal conditions—cool and dark—however, argan oil can oxidize rapidly.

†Most rural villages, including those villages in our sample, have easy access to a local primary school, but secondary schools are farther away; therefore, the transition from primary to secondary school requires a substantial investment. Although 47% of girls and 67% of boys in rural areas attend primary school, only 8% of girls and 17% of boys attend secondary school (30).

‡Cutting live argan trees and branches is illegal. The argan wood used as a fuel source is mostly collected as dead or dying branches, which may be more readily available with more aggressive harvesting techniques. Although concrete evidence is obviously sparse, anecdotal evidence suggests that at least some of this collected argan wood is not dead.

§The 2.40-point estimate from Table 1 indicates the increase in girls' enrollment as a percentage of the total population. School-aged (5–19 y) girls constitute roughly 16% of the total Moroccan population (31). We can adjust the point estimate to approximate the increase in girls' enrollment as a percentage of school-aged girls as 0.024/0.16 = 15%. Relative to a commune with no argan forest, one with 65% coverage, thus, experienced roughly a 10% increase in girls' enrollment.

¶Local exploitation through overgrazing and urban encroachment in a few locations is the most likely cause of any negative canopy trends. Although irrigated agriculture expanded in some southern portions of the forest before the argan boom, it has affected the argan forest much less in recent years.

Table 1. Results of primary and secondary school enrollment estimation for rural communes in Essaouira Province from 2000 to 2005

	1-y difference			4-y difference		
	Girls	Boys	Total	Girls	Boys	Total
Argan						
Coefficients	−0.052	−0.29	−0.33	−0.22	−1.18	−1.33
P value	0.64	0.0068	0.053	0.64	0.021	0.094
Argan × weak education infrastructure						
Coefficients	0.59	0.46	1.04	2.40	1.83	4.23
P value	0.0038	0.075	0.019	0.0052	0.090	0.024
Argan × weak other infrastructure						
Coefficients	0.040	0.11	0.14	0.16	0.45	0.57
P value	0.59	0.19	0.31	0.60	0.25	0.37
Weak education infrastructure index						
Coefficients	−0.066	−0.061	−0.13	−0.27	−0.25	−0.51
P value	0.085	0.16	0.079	0.100	0.18	0.091
Weak other infrastructure index						
Coefficients	−0.034	0.0087	−0.027	−0.13	0.035	−0.091
P value	0.34	0.82	0.70	0.39	0.83	0.76
Trend						
Coefficients	−0.36	−0.19	−0.56			
P value	0.000	0.000	0.000			
Constant						
Coefficients	724.8	377.9	1,116.2	0.44	0.59	1.02
P value	0.000	0.000	0.000	0.000	0.000	0.000
N	179	179	178	44	44	43
R^2	0.47	0.15	0.40	0.18	0.20	0.19

The dependent variable is the change in the number of students enrolled in both primary and secondary schools as a percent of commune population (measured in percentage points). Weak education and other infrastructures are constructed as factor analytic indexes using commune-level access to education, accessibility through different forms of transportation, and access to electricity and running water. The SEs used to compute the *P* values were clustered at the commune level. Note that 2- and 3-y differences yield similar results.

To this end, we zoom in on pixels in or near the argan forest and assess changes in canopy trends in greater detail. As before, we use the argan boom as the treatment, where only pixels with (preboom) argan forest coverage are treated. Nonargan pixels that contain different tree and shrub species (e.g., *Acacia*, *Juniperus*, and *Tetraclinis*) serve as pseudocontrol pixels, because they were subject to the same climatic pressures as the argan forest but not the anthropogenic changes induced by the argan boom. After differencing the estimated pre- and post-1999 canopy trends for each pixel, we compare trend changes for argan and nonargan pixels (Fig. S3). We match argan forest pixels with similar nonargan forest pixels nearby and estimate the average effect of the argan boom on (treated) argan forest canopy based on the pairwise comparison of these matched pixels.[‖] Although there is some variation in statistical significance across different matching configurations (Table 2), pixels treated with booming argan prices experienced a decline in NDVI relative to similar pixels with nonargan tree and shrub species. Because we are interested in testing the impact of the argan boom on the argan forest (and not its impact on nonargan forest were it converted to argan forest), the average treatment effect on the treated is most relevant and is significant for all of our matching configurations. Both the magnitude and significance of these impacts are greater when we match pixels with more than 40% argan cover to those pixels with nonargan forest. Booming argan markets have certainly not improved the argan forest and may have even induced more degradation, particularly in northern locations.[**]

These household- and landscape-level analyses offer complementary tests of the win–win claims of poverty alleviation and biodiversity conservation. The household data allow for rigorous tests of welfare impacts, but evidence of forest impacts can only be deduced from households' reported actions. In contrast, the landscape-level analysis offers less robust but suggestive evidence of benefits to girls' education, while providing a more rigorous test of the impact of the boom on the argan forest. Combined, these results suggest that locals are benefiting from the argan boom in ways that may improve women's welfare and alleviate persistent rural poverty, but this benefit is at the risk of degrading the forest and the biodiversity that it sustains. Unless locals' short-term obsession with fruit collection matures into longer-term productivity and sustainability concerns, rural poverty reduction may itself be a short-term benefit of the argan boom.

Discussion: Dynamic Dimensions of Local Welfare and Forest Impacts

The argan oil case offers an excellent opportunity to investigate the dynamic linkages between local benefits and conservation gains. Consider the interplay between locals' response to argan fruit price appreciation, argan markets, and forest impacts. In 1999, high-value argan oil extractors insisted on purchasing only

[‖]We have performed an additional analysis that offers a complementary perspective on these trend changes and yields qualitatively consistent results. For example, we have pooled the trend changes for all pixels and estimated a spatial error regression model with percent argan cover and other controls as explanatory variables. The coefficient on percent argan cover is negative—indicating that a higher dosage of argan cover is associated with a more negative trend change during the argan boom—and weakly statistically significant (*P* value = 0.15).

[**]Note that, whereas Fig. 1 displays the value of the NDVI trend coefficient, Table 2 is based on the difference in this trend before and after the onset of the boom. Thus, although Fig. 1 suggests that negative NDVI trends have been spatially concentrated in the northern forest since the onset of the boom, Table 2 suggests that the change in trends has been negative on average in the argan forest relative to nonargan forest.

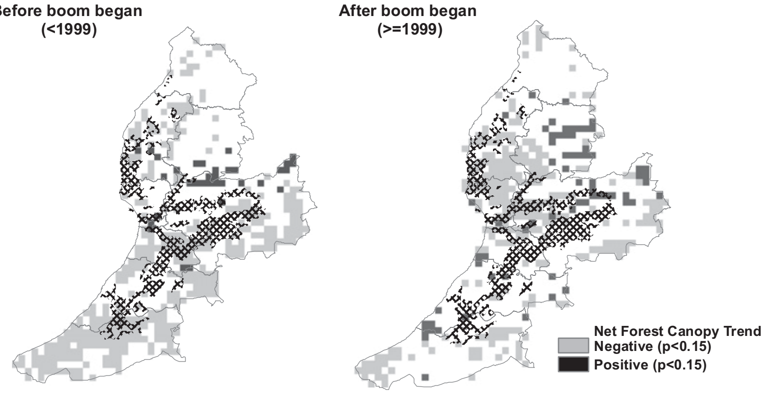

Fig. 1. Estimated pixel-level trends for dry season NDVI net of rainfall effects. Because trees are often the only dry season vegetation, these dry season NDVI trends track forest canopy changes. *Left* shows these trends before the argan boom started (i.e., before uses years 1981–1998). *Right* shows these trends after the argan boom started (i.e., after uses 1999–2009). Negative and positive net forest canopy trends are shown for statistically significant trend coefficients. Pixels with insignificant trend coefficients are depicted as blank. Cross-hatching indicates the extent of the argan forest in 1994.

whole fruit in local markets as a guarantee that the kernel inside had not passed through a goat's gut (40). Since then, rapid appreciation of argan fruit prices has prompted locals to collect fruit by hand and prevent their goats from ingesting whole fruit. Thus, there are far fewer goat kernels in local markets. Knowing this fact, high-value extractors are increasingly willing to purchase kernels in spot markets, which have become nearly as active as those markets for argan fruit. Moreover, this change has increased the volume of kernels sold as well as doubled the price premium of kernels over fruit between 2005 and 2009.[††] In short, initial market changes induced a behavioral response that resolved a market for lemons problem (41) and enabled the emergence of high-value kernel markets. Because the laborious task of extracting the kernel has yet to be mechanized, this induced kernel market may be the most promising path from high-value argan markets to rural poverty alleviation.

Next, consider the dynamic pressures on tenure institutions in the argan region. Booming argan markets have, not surprisingly, led to greater privatization pressure (11, 42). In the argan forest, unique tenurial arrangements (*SI Discussion* and Fig. S2) give important nuance to implications of these privatization pressures. Households that previously only had seasonal usufruct rights to specific tracts of the forests are now enclosing these tracts to deny others access all year long. These barriers, which are technically allowed if temporary, are becoming increasingly permanent. Because private usufruct rights encroach on collective grazing rights during the nonharvest season, the forest may well benefit from better management—albeit at the cost of excluding poor households with limited private productive resources from these forest commons. The poverty of these households may persist despite booming argan markets.

From a conservation perspective, a key dynamic involves the apparent mismatch between locals' conservation incentives and the long-run sustainability of the argan forest. Although locals are now less likely to let their goats browse in the tree canopy, this forest-friendly change is motivated more by immediate concerns about the fruit harvest than by any longer-term concern for tree or forest productivity. Goats still regularly climb and browse trees outside the fruit harvest season, when most trees are treated as an open access resource, and therefore, they continue to tax the forest. Ever-growing goat herds, thus, remain a concern. This mismatch between private incentives and sustainability of the forest not only bodes poorly for the argan forest in general but interacts with drought cycles and more aggressive fruit harvesting in potentially negative ways. Although the argan tree is well-adapted to arid conditions and can survive in a dormant state for several years during extreme drought, it is quite vulnerable during lesser drought conditions that do not trigger this dormant response. Locals and their goats generally exploit the argan tree more heavily during such episodes of moderate drought, because other options dry up before the argan tree goes dormant—a dependence that can only increase as households shift their livelihoods more heavily to argan fruit. As fruit production falls during these periods, harvesting tactics are likely becoming even more aggressive. Precisely, this scenario played out in 2008—a year of low fruit production, high fruit prices, conflicts among collectors, and frequent and aggressive fruit harvesting. Although the argan tree is robust to many pressures, recovery from these episodes of intense climatic and exploitation pressures can be painfully slow. Because it serves as foundation species for over 1,200 species (7), this cyclical and intensifying pressure on the argan tree threatens the broader biodiversity of the *Acacia–Argania* ecoregion.

Materials and Methods

We surveyed a representative sample of rural households in Essouira Province in 1999 and again in 2007 (Fig. S1). Analysis of the 1999 data, collected before the argan boom, suggested that differentiation in argan oil markets would prevent locals from tapping high-value markets directly (40) and that conservation gains might be disappointing, because the slow growth of the tree implies low returns to local conservation investments (43). We compare our 1999 and 2007 data to evaluate the welfare effects of induced changes in households' argan activities. Specifically, we assess how households' access to argan fruit in 1999—an indicator of *ex ante* potential to benefit from the argan boom—affected three types of household welfare outcomes: consumption (spending at market), assets (livestock holdings), and children's education (complete details in ref. 29).

Our broader mesolevel analysis exploits differences in forest coverage across communes and pixels to assess the impact of the argan boom on two response variables: changes in educational outcomes and forest canopy density. As the treatment, we use booming argan markets after 1999. Initial argan forest coverage (as collected in a 1994 Moroccan forest inventory) indicates the dosage of the argan boom treatment in a given location.

In the commune-level education analysis, we use primary and secondary school enrollment data from Essaouira Province disaggregated by sex and collected annually from 2000 to 2005, a period of rapid appreciation in argan prices that roughly corresponds to our household-level data. Although we can

[††]This price premium for kernels over fruit is driven by two countervailing factors. First, it is positive because of the value added from kernel extraction, an onerous task that is carried out by women and has yet to be mechanized very successfully. The second and countervailing pressure is the risk that kernels have been digested by a goat, which reduces the premium of kernels over fruit. As goat-ingested kernels become more scarce in local markets, this second risk penalty diminishes, and the kernel premium increases.

Table 2. Average treatment effects for the presence of argan forest on the change in dry season NDVI trend since the onset of the argan market boom

	1	2	3	4	5	6
Exclude pixels below median argan cover*	No	No	No	Yes	Yes	Yes
Weights on matching covariates†	Equal	Proximity	Proximity	Equal	Proximity	Proximity
Exclude lowest 25% of mean dry (NDVI)‡	No	No	Yes	No	No	Yes
Average treatment effect						
Coefficients	−0.0040	−0.0027	−0.0028	−0.0050	−0.0056	−0.0064
P value	0.046	0.17	0.19	0.030	0.014	0.011
Average treatment effect on treated						
Coefficients	−0.0051	−0.0043	−0.0044	−0.0078	−0.0074	−0.0080
P value	0.033	0.067	0.086	0.008	0.008	0.007
n	493	493	444	335	335	302

These estimates are based on nearest-neighbor matching using geographic proximity, mean dry season NDVI, and coefficient of variation of NDVI as matching covariates. *P* values are based on heteroskedastic SEs.

*Percent argan cover indicates the amount covered by argan forest as indicated by the 1994 argan forest inventory. Note that this measurement is the extent but not the density of the argan forest. Among pixels with any argan cover, median percent argan cover is 40%. Matching treated argan pixels with more than 40% argan forest cover with control pixels with nonargan forest provide a cleaner comparison of argan and nonargan forest pixels.

†Equal indicates nearest-neighbor matching with equal weights on all matching covariate. Proximity indicates matching with heavier weight on geographic proximity than on mean dry season NDVI and coefficient of variation (NDVI).

‡Low mean dry season NDVI indicates little or no tree and shrub coverage whether argan or nonargan. Excluding the lowest quartile of pixels based on mean dry season NDVI effectively excludes nonforested or sparsely forested pixels.

measure the transition from primary to secondary school for each child in our surveyed households, we can only measure total enrollment by sex with the commune data, because these data do not distinguish between primary and secondary students. We regress changes in enrollment as a percentage of commune population on the percent of the commune covered by argan forest in 1994, two commune-level infrastructure indexes, interaction terms between forest cover and infrastructure indexes, and a time trend. We construct the infrastructure indexes using factor analysis (*SI Materials and Methods*) and include them as controls, because rural enrollment decisions are heavily shaped by accessibility to schools and geographic isolation (e.g., accessibility by different forms of transportation, availability of electricity, etc.). Furthermore, the impact of argan benefits on these enrollment decisions may vary according to local infrastructure: increased household income may partly compensate for weak infrastructure and therefore, could have a bigger marginal impact on enrollment in places with poor infrastructure. To test whether the enrollment impact of the argan boom is mediated by infrastructure, we include the interaction of argan cover and these indexes in our specification. We estimate this model separately by sex for 1- and 4-y enrollment differences. The lack of similar panel data prevents us from conducting this kind of commune-level analysis for other provinces in the argan region or using measures of household consumption, poverty, or livestock as dependent variables.

We use our NDVI analysis to evaluate anthropogenic changes in forest and canopy density caused primarily by local exploitation of the forest, especially grazing. Based on the validation exercise described in *SI Materials and Methods*, we are confident that NDVI is a robust measure of canopy coverage (Table S1). We compare changes in the argan forest to changes over the same time period in nearby nonargan forest using an empirical model that is relevant to argan trees, nonargan trees, and shrubs alike—all of which function as foundation species in very similar ecosystems. Our approach relies on NDVI differencing, which has been shown to measure landscape changes in regions more arid and more sparsely vegetated than the argan forest (44, 45). In contrast to earlier work that assessed changes throughout Morocco using NDVI (46), we focus on the argan forest region, incorporate rainfall data, and isolate the NDVI trend for the forest canopy by focusing on dry season trends, during which there is virtually no vegetation besides tree canopies. The data that we use consist of 10-d composite NDVI data covering 29 y (1981–2009), which have a resolution of 8 × 8 km and were derived from advanced very high-resolution radiometer available from the US Geological Survey (47). The data were based on composite images generated by the National Oceanic and Atmospheric Administration. As in other settings (37), we expect the NDVI to be strongly correlated with species richness and biomass in the argan forest region, because in the dry season, it reflects forest and canopy density of foundation species in these ecosystems.

In the arid argan forest region, rainfall is critically important to vegetative productivity. On average, over 90% of precipitation in the region falls during the wet season between November 1 and May 31. Although the forest floor can produce various grasses and rain-fed farmers can grow a meager barley crop during these months, the floor of the forest—whether argan or nonargan—is largely void of vegetation during the dry season. We leverage the fact that trees and shrubs are the only vegetation in the forest during the dry season to isolate the NDVI trend for the forest canopy. Specifically, we estimate an autoregressive switching regression model for each pixel that takes the following form (Eqs. **1** and **2**):

$$\begin{aligned} NDVI_{it} &= \beta_0 + \beta_1 Rain_{it} + \beta_2 CumRain_{it} + Wet_i(\beta_3 t) \\ &\quad + Dry_i\left(\beta_4 CumRain_{i,t-1} + \theta t\right) + \varepsilon_{it} \text{ and} \\ \varepsilon_{it} &= \sum_{s=1}^{K} \rho_s \varepsilon_{i-s} + u_{it} \end{aligned} \qquad \textbf{[1 and 2]}$$

where $Rain_{it}$ is contemporaneous rainfall measured at a provincial weather station for the 10-d period t and season i, *CumRain* is cumulative rainfall since the beginning of the last wet season, *Wet* and *Dry* are wet and dry season dummies, respectively, and t is a trend variable. In this specification, the switching regression on trend enables us to focus specifically on the dry season trend (θ), while controlling for factors that affect NDVI in both seasons as well as season-specific factors such as lagged cumulative rainfall, which directly affects the forest canopy. During the dry season, vegetation captured by the NDVI is contained almost entirely in the forest canopy, and therefore, θ specifically captures changes in the forest canopy. We use a stepwise procedure to determine the order of autoregression. Given the distinct seasonality of rainfall in the region, this procedure yields a high order of autoregression (K = 39). The complete time series includes over 800 observations for each of 7,765 pixels. We use the onset of the boom in 1999 to split this data into preboom and boom phases and estimate the dry season trend over these two sets of years for each pixel separately (Fig. 1).

To formally test how the boom has affected the argan forest, we use the two estimated trend coefficients for each pixel to construct a differential trend variable $\Delta\hat{\theta}_z = \hat{\theta}_z^{\geq 1999} - \hat{\theta}_z^{<1999}$, which captures the change in the estimated canopy trend for pixel z associated with the onset of the argan boom in 1999.[‡‡] Next, we compare $\Delta\hat{\theta}_z$ for each pixel in the argan forest to one in

‡‡Graphically, $\hat{\theta}_z^{<1999}$ indicates the linear slope of the forest canopy from 1981 to 1998 (conditional on all other variables in Eqs. **1** and **2**), and $\hat{\theta}_z^{\geq 1999}$ is the conditional slope of the canopy from 1999 to 2009. $\Delta\hat{\theta}_z = \hat{\theta}_z^{\geq 1999} - \hat{\theta}_z^{<1999}$, thus, indicates the change in slope between these two periods (i.e., before and during the argan boom).

similar and nearby nonargan forest drawn from pixels adjacent to the argan forest. Because the pixels in each of these pairs are subject to comparable climatic and other pressures[§§] but only the argan pixel is affected by booming argan markets,[¶¶] we can pool all these pairwise comparisons together to estimate an average treatment effect of the argan boom on the argan forest (Table 2).

Before matching argan and nonargan pixels, we exclude pixels that include irrigated land and urban fringes. We use nearest-neighbor matching based on geographic proximity, mean dry season NDVI, and the coefficient of variation of NDVI. This matching process pairs pixels in the argan forest with nearby pixels with other tree and shrub species that otherwise have similar vegetative density. We use these matched pairs to estimate the average treatment effect of the argan boom on argan forest density using the nonargan pixels with other species as controls. The average treatment effect on the treated indicates the impact of the argan boom on the argan forest relative to its impact on nonargan forest. Because this test is a relative test, it captures genuine improvements in argan forest, displaced degradation in nonargan forest, or both, which makes finding a positive (negative) impact of booming argan markets on argan forest easier (harder). For example, if locals on the edge of the argan forest move their livestock to the nonargan forest in the wake of rapid argan price appreciation to increase their fruit collection, this increased pressure would decrease the nonargan forest canopy trend relative to the neighboring argan forest. As one of the three robustness tests in Table 2, we estimate treatment effects excluding pixels with sparse tree or shrub cover (i.e., those pixels in the lowest quantile of mean dry season NDVI). Notice: Although this work was reviewed by EPA and approved for publication, it may not necessarily reflect official agency policy. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

[§§]This nearest-neighbor matching controls for other geographically concentrated forest pressure that is common to both argan and nonargan forest (e.g., growth pressures on urban fringes, agricultural conversion pressures near access to irrigation, etc.).

[¶¶]If the argan tree was domesticated and nonargan forest was converted to argan forest in response to the argan boom, this assumption would not hold. Because this scenario is not the case and argan reforestation was totally nonexistent in the past decade, this assumption is easily defensible.

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