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Adoption of Cover Crops under Uncertainty: A Real Options Approach

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Abstract

This paper applies a real options framework to investigate the effects of yield and price uncertainty on the decision to adopt cover crops in cotton production. Based primarily on data from a 29-year field experiment in West Tennessee (1984-2012), we evaluate the decision to invest in two cover cropping practices — hairy vetch and crimson clover — within conventional till and no-till cotton production systems. The real options approach considers farmers' cover crop decisions in the presence of: (1) cotton yield and price uncertainty, (2) flexibility in potentially delaying cover crop adoption to later periods, and (3) partial irreversibility due to the sunk costs involved in adopting combined cover crop and tillage systems. The main results of the analysis show that while traditional investment analysis using net present value (NPV) indicates that immediate adoption of cover crops is profitable in the long run, the optimal strategy in a real options framework is for cotton farmers to delay cover crop adoption for at least 5 years until new information that reduces uncertainty is available or the sunk cost of adoption decreases.

Keywords: Cover Crop, Real Options, Uncertainty, Dynamic Programming
JEL Codes: Q11, Q16, C61

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1 Introduction

In recent years, heightened interest in soil health has been stimulated by increasing awareness that the soil is a critical component of the earth's biosphere and that it plays a vital role in the sustainable functioning of the global food system (Stevens (2018)). For example, soil erosion problems on cropland is of particular interest because it fundamentally affects soil health and, in turn, agricultural productivity. Nearly one-third of the world's cultivable land has been lost due to soil erosion, and it continues to be lost at a rate of more than 10 million hectares per year, which puts significant amount of pressure on cropland sustainability, environmental quality, and the condition of earth's natural resources (Pimentel et al. (1995)).

Adoption of winter cover crops offer a practical means for mitigating soil erosion and preserving agricultural productivity by building up soil surface residue and increasing organic matter in soils. According to the 2016 annual cover crop survey by the Sustainable Agriculture Research and Education (SARE) program and the Conservation Technology Information Center (CTIC), 86% of respondents find that improvement in soil health is the foremost benefit from adopting cover crops, while increasing cash crop yield consistency was the second highest-rated cover crop benefit. More than half (54%) of the surveyed farmers believed that soil health benefits from cover crops can be realized even in the first year of use. Despite the potential environmental and agronomic benefits of using winter cover crops, adoption rate of this agricultural practice has been low across the United States (US) (Boyer et al. (2018)). Cover crops were only used on 1.7% of all US cropland in 2010-2011, and only about 4% of farmers adopted cover crops on some portion of their fields (CTIC and SARE (2016)). The 2017 US Census of Agriculture reveals that cover crop acres are only roughly 3.9% of all crop land acres (Zulauf and Brown (2019)).

The SARE-CTIC survey further suggest that the major economic concerns about cover crops for non-users are the uncertainty about economic returns and high costs of adoption. As with many innovative agricultural practices, cover crops come with costs of adoption, both direct and indirect. Additional direct costs associated with cover crop adoption include

seed costs, additional labor, machinery, and repair costs for cover crop planting operations (and, where necessary, for termination operations). Indirect costs include effects on cash-crop management and foregone opportunities. Opportunity costs of time and money are important indirect costs of cover cropping. Utilizing cover crops require the producer to actively manage cropping systems on a year-round basis. While cover crops are not managed as intensively as cash crops, there is a marked difference in conventional fallow versus cover-crop management. Thus, additional cover crop training and education may be a prerequisite to adoption. Hence, time spent on learning about this new practice could possibly be used toward other ends, and thus adopters may potentially incur a high opportunity cost for their time (Bergtold et al. (2017)). Foregone income from cash crop yields is also a significant opportunity cost of cover crop adoption, given that there is a possibility that there is no yield and revenue benefit in the initial years of cover crop use (Myers et al. (2019)).

These observations are consistent with research that emphasizes the importance of analyzing the effects of net return uncertainty and irreversible sunk costs on the timing of the decision to adopt a new agricultural technology. If a new, more sustainable practice requires a significant financial outlay that cannot be easily recouped later (e.g., like purchase of a new farm equipment or building farm infrastructure) or there is substantial time commitment to implement the practice (i.e., with a high opportunity cost), the farmer is more likely to wait in order to improve his certainty that this investment will pay off in the future. Similarly, when there is uncertainty in prices or crop yields in the future, it may be to the farmer's advantage to wait until he has more information about potential long-term price or yield outcomes (Miller et al. (2012)).

The main purpose of this study is to analyze the effects of yield and price uncertainty on the decision to adopt winter cover crops in cotton production. To accomplish this objective, we apply the basic option value theory of investment under uncertainty (also called the real options framework) (Dixit and Pindyck (1994)). In particular, the empirical context is to investigate the optimal timing decision for investing in two kinds of cover crops — hairy

vetch (HV) and crimson clover (CC) — within conventional till and no-till cotton production systems using a 29-year field experiment data set in West Tennessee (1984-2012).

Much of the recent economic literature that analyze the profitability of planting cover crops treat it as a short-term annual adoption decision and usually use short-term field trial or survey data in their evaluations. Hence, most of these studies utilize partial budget type analysis to ascertain whether adopting winter cover crops generate positive annual net returns (i.e., profit increasing changes due to cover crops (say, from higher yields/revenues) is larger than the profit decreasing changes (like increasing cost)) (see, among others, Boquet et al. (2004); Dunn et al. (2016); Snapp et al. (2005); Triplett and Dick (2008); Plastina et al. 2018a, 2018b; Myers et al. (2019)). Cover crops could increase producer net returns through higher yields and reduced N fertilizer costs with N fixing cover crop species, but establishment and termination of the cover crop increase costs. In general, results from previous studies that estimate annual net returns to cover crop adoption are largely mixed for a variety of row crops (including cotton) — some find positive net returns, while others find negative net returns (i.e., for cotton see Varco et al. (1999); Larson et al. (2001); Hanks and Martin (2007); Foote et al. (2014); Zhou et al. (2017)). This inconsistency in economic results may be a factor with regards to the relatively low adoption rates for cover crops in the US.

Nonetheless, a number of studies have recognized that longer-term use of soil health practices like cover crops may be required before one realizes consistent positive annual net returns from adoption (Soule et al. (2000); Boyer et al. (2018); Myers et al. (2019)). Agronomic studies that have examined long-run use of cover crop and no-till practices have shown that soil and yield benefits from these soil health practices accumulates over several years of continuous use (Richter et al. (2007); Karlen et al. (2013); Mbuthia et al. (2015)). Looking at annual returns to cover crop adoption, Myers et al. (2019) highlighted that short-term use of cover crops (1-2 years) do not usually result in positive net economic returns (i.e., upfront costs in the short-run outweigh the benefits), but medium- to long-term use of

this practice (i.e., 3 years or more) is necessary for one to see positive net returns.

The argument is that use of cover crops (and other soil health practices) do not typically result in immediate (short-run) improvement in soil health (e.g., large immediate improvement in soil organic carbon is not possible naturally). But over time, with at least three or more years of cover cropping, the improvement in soil health is expected to result in yield benefits that can overcome its costs (Myers et al. (2019); Cai et al. (2019)). In light of these observations, the decision problem for soil health practices like cover crops and no-till practices can be viewed as a long-term investment, and economic evaluation of these practices requires assessing the net present value (NPV) of the streams of benefits and costs over time (Larson et al. (2001); Zhou et al. (2017); Boyer et al. (2018)). For example, Boyer et al. (2018) conducted simulation-based investment analysis of several cover crop and tillage practices over a long-run period. They find that risk neutral, profit-maximizing cotton producers would prefer conventional till planting and not planting a cover crop, while risk averse producers would prefer no-till planting with no cover crops.

If soil health practices like cover crops and no-till are considered a long-term investment, then a real options approach would be appropriate in analyzing the economics of this decision since it is a comprehensive dynamic-stochastic model that accounts for a number of important behavioral factors that can affect the decision, such as: uncertainty in the investment returns, the sunk costs associated with establishing the practice, and the flexibility of delaying practice implementation to future years. Hence, the main contribution of the present study is the application of the real options framework in a long-term economic analysis of cover crops that provides more insights on how the aforementioned behavioral factors affect the adoption decision. To the best of our knowledge, this is the first study that have used this analytical lens to analyze decisions regarding soil health practices. Note, however, that the utility of the real options approach in analyzing agricultural technology investments (in general) have already been pointed out in the past. For example, Marra et al. (2003) indicated that there is usually an "option value" in waiting to invest on an

agricultural technology, especially if there is uncertainty about future payoffs and there is partially irreversible sunk costs (and there is a probability of not being able to recover the initial investment cost). Hence, couching the farmer's decision problem as having the option to wait before adopting (while taking uncertainty and sunk costs into account) can reveal additional barriers to adoption that are obscured in the straightforward financial analysis that only compares the NPVs of net benefit streams over time.

Although there have been no previous studies that have examined the soil health investment decision using the real options approach, there are past studies that utilized the real options framework to analyze investments in other types of agricultural technologies. Purvis et al. (1995) apply this method to dairy farmer's investment in new waste management technology and analyze how uncertainty and irreversibility affect producers' responsiveness to agricultural technologies. Chavas (1994) examine the effects of sunk cost and temporal uncertainty on the implicit rental value of capital and investment, as well as entry-exit production decisions. Khanna et al. (2000), used the option-value approach to examine the impacts of uncertainty about output prices and expectations of declining fixed costs on the optimal timing of investment in site-specific crop management technology. Seo et al. (2008) analyze the entry and exit thresholds for the low-energy precision application irrigation system in cotton farming in the Texas High Plains using a real options approach. Tzouramani and Mattas (2009) apply a real options approach to evaluate an adoption decision by farmers of organic-farming techniques under uncertainty and risk in Greece. Musshoff (2012) develops a real options model to examine when farmers should convert agricultural land to short rotation coppice (SRC) in Northern Germany. Ihli et al. (2014) analyze the (dis)investment behaviour of farmers to adopt irrigation technology and conclude that the real options approach predict the decision behaviour of farmers better than the classical investment theory by incorporating an optimal stopping framework in analysing the timing of (dis)investment.

Therefore, the present study complements the existing agricultural technology literature that have used the real options framework in analyzing adoption decisions. Findings from

the present study suggest that it may be preferable to delay adoption of cover crops (e.g., crimson clover in particular) for at least five years under no-till cotton production systems. Longer delays in adoption is observed under conventional tillage due to the higher sunk costs associated with cover crop implementation in this system. Hence, uncertainty in future net returns and sunk costs involved in continuous long-term use of cover crops are likely important factors that can also explain the current low levels of cover crop adoption. More information that can minimize uncertainty in returns and perhaps technological innovations that can lower cost of implementation can shorten the delay in adoption and improve cover crop adoption levels.

The rest of this article is organized as follows. Section 2 describes our theoretical model — mainly to present how the cover crop investment decision fits in a real options framework. Section 3 describes the field trial data, presents a descriptive analysis, and outlines our empirical strategy. The main empirical results are presented and discussed in Section 4. Section 5 concludes and discusses policy implications, limitations, and future research.

2 Theoretical Model

As discussed in the previous section, the adoption of winter cover crop can be considered as an investment decision given the long-term dynamic nature of the problem. A farmer will decide to invest in cover crops and implement this new agricultural practice only if the investment prove to be profitable. In contemplating such a decision, a farmer who wishes to pursue the possibility of adopting a cover cropping practice has two options: adopt the new practice now or wait and see if conditions will change and become more attractive in the future.

According to a traditional NPV methodology, a decision on whether to make a long-term investment on continuous cover crop use is based simply on a comparison of the investment fixed cost of the new practice (I) and the present value of its net quasi-rent (V_t). Under

conditions of certainty, we can calculate V_t as follows:

$$V_t = E(P_t)(Y_t^C - Y_t^N) - (X_t^C - X_t^N) \tag{1}$$

where P_t is crop price at time t, Y_t^C and Y_t^N represent the yield from cash crop production with and without cover crops, and X_t^C and X_t^N are the variable costs for the production system with and without cover crops. The present value (at $t = 0$) of the expected quasi-rent differential is therefore given by:

$$V_0 = \int_0^T e^{-\rho t} V_t dt > 0 \tag{2}$$

Hence, under the traditional NPV approach, the practice is adopted only when the NPV of the quasi-rent differential is larger than or equal to the investment costs; that is, $V_0 \geq I$.

However, in the case of a decision to invest in long-term winter cover crop use, it is apparent that the assumptions required for straightforward application of the NPV approach are violated since there is usually uncertainty in net returns to cover crop adoption, there is a sunk cost to incorporating cover crops in production systems, and producers have the temporal flexibility to decide when to adopt the practice. Hence, the simple NPV rule does not directly fit the nuances of the current empirical context and would not be able provide insights on the role of uncertainty, sunk costs, and temporal flexibility on the cover crop adoption decision. The present value of the expected stream of benefits from a cover crop investment must not only be positive, but also must exceed the cost of the new practice by an amount at least equal to the value of keeping the investment option alive (Dixit and Pindyck (1994)).

Taking option values into account, a profit-maximizing farmer who wishes to invest in the long-term use of the winter cover crop practice has the option of adopting at $T = 0, ..., \hat{T}$ in order to maximize the expected NPV of the quasi-rent differentials over time. Let V_T denote the present value at time T of the expected quasi-rent differential due to adoption. In this

analysis, we assume that both price and yield uncertainty are captured in overall revenue differentials. Therefore, we assume V_T is stochastic and follows a geometric Brownian motion process:

$$dV = \alpha V dt + \sigma V dz \tag{3}$$

where α is the drift(trend) rate, σ is the volatility rate, dt is the small time increment, and dz is the continuous-time stochastic Wiener process defined as $dz = \epsilon_t \sqrt{dt}$, where $\epsilon_t \sim N(0,1)$.The expected value of the Wiener process is $E[dz] = 0$ and its variance is $E[(dz)^2] = dt$ (Dixit and Pindyck (1994)).

The objective of a risk-neutral, profit-maximizing farmer is to find an optimal adoption time T^* to pay the sunk cost I to implement a cover cropping practice whose value V maximizes the NPV of profit subject to the stochastic movement of a random quasi-rent differential over time; that is:

$$F(V) = \max_{T^*} E[(V_T - I)e^{-\rho T}] \tag{4}$$

subject to Eq. (3), where ρ is the discount rate. For this problem to be tractable, we must also assume that $\alpha < \rho$, otherwise the integral in Eq. (2) could be made indefinitely larger by choosing a larger T.

Since the quasi-rent V evolves stochastically, we will not be able to solve Eq. (4) analytically to produce an adoption timing point T^*. Instead, our adoption rule will take the form of a critical value V^* such that it is optimal to adopt once $V \geq V^*$. Because the adoption opportunity, $F(V)$, yields no net benefit flows until long-run cover crop adoption is undertaken, the stochastic dynamic optimization (Eq.(4)) can be written as the following Bellman equation:

$$\rho F dt = E[dF] \tag{5}$$

Eq. (4) implies that over a time interval dt, the total expected return from the investment in long-term cover crop use, $\rho F dt$, is equal to its expected rate of appreciation from holding

the option to adopt in the future. Then we can expand dF using Ito's Lemma:

$$dF = F'(V)dV + \frac{1}{2}F''(V)(dV)^2 \tag{6}$$

Substituting Eq. (3) for dV into the expression above and we know $E(dz) = 0$, we can get:

$$E(dF) = \alpha V F'(V)dt + \frac{1}{2}\sigma^2 V^2 F''(V)dt \tag{7}$$

Hence the Bellman equation becomes:

$$\frac{1}{2}\sigma^2 V^2 F''(V) + \alpha V F'(V) - \rho F = 0 \tag{8}$$

In addition, $F(V)$ must satisfy the following boundary conditions:

$$F(0) = 0 \tag{9}$$

$$F(V^*) = V^* - I \tag{10}$$

$$F'(V^*) = 1 \tag{11}$$

Condition (9) means if V goes to zero, it will stay at zero. Therefore the option to invest will be of no value when $V = 0$. The other two conditions arise from considerations about the optimal time to make the investment. Condition (10) says that upon investing, the farmer can receive a net profit $V^* - I$. Condition (11) is the "smooth-pasting" condition since if $F(V)$ were not continuous and smooth at the critical point V^*, one could do better by exercising at a different point (Dixit and Pindyck (1994)).

Since the second-order homogeneous differential Eq. (8) is linear in the dependent variable F and its derivatives, the general solution is a combination of any two independent solutions. The solution form of the homogeneous part is $F(V) = Ay^\beta$, where A is the

constant to be determined if β satisfies the fundamental quadratic equation:

$$\frac{1}{2}\sigma^2\beta(\beta-1)+(\rho-\delta)\beta-\rho=0 \tag{12}$$

where δ is the risk- and growth- adjusted discount rate, denoting the difference $\rho-\alpha$. The respective positive and negative roots of this quadratic equation are:

$$\beta_1=\frac{1}{2}-\frac{(\rho-\delta)}{\sigma^2}+\sqrt{[\frac{(\rho-\delta)}{\sigma^2}-\frac{1}{2}]^2+\frac{2\rho}{\sigma^2}}>1 \tag{13}$$

and

$$\beta_2=\frac{1}{2}-\frac{(\rho-\delta)}{\sigma^2}-\sqrt{[\frac{(\rho-\delta)}{\sigma^2}-\frac{1}{2}]^2+\frac{2\rho}{\sigma^2}}<0 \tag{14}$$

so the general solution to Eq. (8) can be written as:

$$F(V)=A_1V^{\beta_1}+A_2V^{\beta_2} \tag{15}$$

In our problem, the boundary condition (9) implies that $A_2=0$, leaving our solution as:

$$F(V)=AV^{\beta_1} \tag{16}$$

where A is a constant to be determined, and $\beta_1>1$ is a known constant whose value depends on the parameter σ,ρ and δ of the differential equation.Then, by substituting Eq.(16) into condition (10) and (11), we find that:

$$V^*=\frac{\beta_1}{\beta_1-1}I \tag{17}$$

and

$$A=\frac{V^*-I}{(V^*)^{\beta_1}} \tag{18}$$

where

$$\beta_1 = \frac{1}{2} - \frac{(\rho - \delta)}{\sigma^2} + \sqrt{[\frac{(\rho - \delta)}{\sigma^2} - \frac{1}{2}]^2 + \frac{2\rho}{\sigma^2}} > 1 \tag{19}$$

Therefore, Equations (16)-(19) gives us the value of the investment to adopt the cover crop practice, and the optimal investment rule — that is, the critical value V^* at which it is optimal to invest. While the traditional NPV rule implies that cover crop adoption occurs when $V \geq I$, the real options method suggests adoption only when $V \geq \frac{\beta_1}{\beta_1 - 1} I$. Also, Eq. (18) implies that $\frac{\beta_1}{\beta_1 - 1} > 1$, and $V^* > I$ with V^* decreasing as β increase. As uncertainty about returns from investing (σ) increases, β becomes smaller and the difference between V^* and I increases and it is optimal to wait longer to invest. When the discount rate increases, β increases, reducing the difference between V^* and I, so it is optimal to invest earlier.

3 Data and Empirical Analysis

Data for this study were collected from a 29-year field experiment (1984-2012) that examines outcomes from a variety of winter cover crops, N fertilization, and tillage practice treatments at the West Tennessee Research and Education Center in Jackson, TN ($35.624°N, 88.845°W$). The soil in the experimental plots was classified as a Memphis silt loam (fine-silty, mixed, active, thermic Typic Hapluadalf), which is a deep, well-drained, moderately permeable soil formed in thick (1.5m) loess deposits (USDA-Natural Resources Conservation Service, 2002). Soils in the Memphis series are common for cotton production in Tennessee and neighboring Mid-South states of Arkansas, Louisiana, and Mississippi.

The experimental design was a randomized complete block design with split-plots and four replications. Using ammonium nitrate, plots were randomly assigned N fertilizer rates of 0 or 33.6 kg N ha^{-1}. Each fertilizer main plot was further split where a no cover crop treatment, a hairy vetch treatment, or a crimson clover treatment is randomly assigned. Plot size for each treatment was 4m wide and 9m long. The same N application rate, winter cover crop, and tillage combination was applied to each plot in each year of the experiment.

The annual P rate was 101 kg P ha^{-1} and the annual K rate was 101 kg K ha^{-1}.

In our analysis here, two cover crop options are evaluated: hairy vetch (HV) and crimson clover (CC). We also have two "no cover crop" treatments: (i) a "control" treatment where there was no cover crops used and no N fertilizer applied, and (ii) a second "control" treatment where no cover crop is used but N fertilizer is applied at 33.6 kg N ha^{-1}. Effectively, we have four treatments overall: (a) no cover crop with zero fertilizer, (b) no cover crop with 33.6 kg N ha^{-1}, (c) HV cover crop treatment, and (d) CC cover crop treatment.[1] Having the second "control" treatment (i.e, where no cover crop is used but 33.6 kg ha^{-1} of N is applied) allows us to examine whether the use of cover crops can also serve as a substitute to chemical N application (i.e., given that the HV and CC cover crop species are natural N fixers that can theoretically reduce reliance on chemical N application). Therefore, given these four experimental treatments, we consider two "comparison scenarios" in our real options analysis: (a) Scenario 1 — where HV quasi-rent differentials are compared against control treatment 1 (control without cover crops and without N fertilizer), and where CC quasi-rent differentials are also compared against control treatment 1 (control without cover crops and without N fertilizer); and (b) Scenario 2 — where the HV quasi-rent differential is compared relative to control treatment 2, and where CC quasi-rent differentials are also compared against control treatment 2 (control without cover crops but with 33.6 kg ha^{-1} N application).[2]

Continuous cotton was planted each year in conventional-till (CT) and no-till (NT) plots in mid- or late May on 17.8-cm row spacing with a population density of 9 to 10 plants m^{-2} following the no cover, HV, and CC winter cover crop treatments. Before planting, no-till treatments received a burn-down application of generic glyphosate [N-(phosphonomethyl)

[1]The 33.6 kg N ha^{-1} is the recommended N rate for cotton in the area when no cover crop is used. For both cover crop treatments (HV and CC), no N fertilizer is applied. The seeding rate for the HV treatment is 22 kg ha^{-1}, and the seeding rate for the CC treatment is 17 kg ha^{-1}. These are the recommended seeding rates for the two cover crop species considered.

[2]In scenario 2, we were not able to compare the CC treatment against control treatment 2 under NT since the estimated quasi-rent for this comparison is negative, and one cannot apply real options analysis in this circumstance. However, this just suggests that the net returns to CC cover crop adoption is less than for control treatment 2, and using CC over control treatment 2 under NT is not advisable at any time.

glycine] and pyrithiobac sodium {sodium 2-chloro-6-[(4,6-dimethoxy pyrimidin-2yl)thio] benzoate} to kill the cover crops and weeds. Cover crops and weeds were destroyed twice for the CT plots. The same cultivar was planted on all plots in each year of the experiment and over the experiment the cultivars were Stoneville 825 from 1984 to 1993, Deltapine 50 in 1994 and 1995, Stoneville 132 in 1996; Deltapine 50 in 1997, Stoneville 474 in 1998, Deltapine 425 in 1999 and 2000, Deltapine 451 from 2001 to 2006, and Phytogen from 2007 to 2012. Seed cotton was mechanically harvested from the two inside rows of each plot and ginned using a one-fifth-scale gin at the West Tennessee Research and Education Center (Jackson, TN) to determine lint yields. Winter cover crops were reestablished in late October after cotton harvest.

A quadratic yield response function is used to represent the functional relationship between yield and N fertilizer. This form has been widely used by researchers to estimate cotton lint yield response to fertilizer and it assumes diminishing marginal yield productivity as the applied N rate increases and attains a yield maximum with subsequent yields decreasing thereafter (Bauer and Roof (2004); Bronson et al. (2001); Boyer et al. (2018); Cochran et al. (2007); Larson et al. (2001); Zhou et al. (2017)). In addition, since the accumulated effects of cover crops on soil health may increase cotton yield, time trends variables are commonly used to capture how yield changes in a long run (Boyer et al. (2018); Finger (2010); Zhou et al. (2017)). The following function was estimated for each winter cover crop and tillage combination:

$$y_{jkt} = \beta_{0jk} + \beta_{1jk}t + \beta_{2jk}t^2 + \beta_{3jk}t^3 + \beta_{4jk}N + \beta_{5jk}N^2 + \beta_{6jk}N \times t + e_{jkt} \tag{20}$$

where y_{jkt} is cotton lint yield of the using cover crop $j(j = 1, ..., J)$ and tillage system $k(k = 1, ..., K)$, N is application rate of N fertilizer. $\beta_0, ..., \beta_6$ are coefficients to be estimated and $e_{jkt} \sim iid(0, \sigma_e^2)$ is an independent and identically distributed random error term. The yield response function was estimated using M-estimation with the ROBUSTREG procedure in SAS 9.4. Parameter estimates for the cotton yield response to N application rate and time

by cover crop and tillage system are shown in Table 1.

The costs of implementing both the HV and CC cover crop options are shown in Table 2. Cover crop seed prices were collected from 2006 to 2012 through personal communication with the Tennessee Farmer Cooperative by some of the study authors. Cover crop seed prices were adjusted to 2012 dollars using Implicit Gross Domestic Product Price Deflator and were \$4.59 kg^{-1} for hairy vetch and \$3.50 kg^{-1} for crimson clover. Machinery [3] and management labor costs were calculated using University of Tennessee Field Crop Budgets for 2018 (Smith et al. (2018)). Management labor costs were assumed to be \$15 ha^{-1}. The relative machinery cost difference between conventional and no-till seeding equipment depends upon machine size. A 20 ft no-till drill costs more than twice as much as a 20 ft conventional drill (Epplin et al. (2005)). Therefore, total machinery costs were \$ 23.73 ha^{-1} for CT, assuming the cover crops were seeded using a 215 horsepower (HP) tractor and 20 ft conventional drill, and were \$ 34.39 ha^{-1} for NT, assuming the cover crops were seeded using a 215 HP tractor and 20 ft no-till drill. The cost of terminating a cover crop was also different for CT and NT. For NT, the cost of a burn-down herbicide application using a 27.4m boom sprayer to kill the winter cover crops before planting cotton was \$47.45 ha^{-1} and the cost of destroying the cover crops for CT cotton using a 215 HP tractor, chisel plow, disk and cultimulcher was estimated to be \$93.17 ha^{-1} (Zhou et al. (2017)). Therefore, for NT, the total cost was \$197.82 ha^{-1} for hairy vetch and \$156.34 ha^{-1} for crimson clover. For CT, the total cost was \$232.88 ha^{-1} for hairy vetch and \$191.4 ha^{-1} for crimson clover (Table 2).

To estimate the quasi-rent differential that farmers can earn with the adoption of the two cover crop options, we first need to assume a cotton price process to forecast future prices while taking uncertainty into account. The historical cotton lint prices were collected from 1929 to 2012 (USDA National Agricultural Statistics Service, 2019). All prices were adjusted to 2012 dollars using the Implicit Gross Domestic Product Price Deflator (U.S. Bureau of Economic Analysis., 2019). To determine whether cotton price process is stationary or

[3]The machinery cost estimates are provided as an estimate of cost of ownership and operation for specified pieces of machinery that would be available to a "representative" row-crop farm in Tennessee.

non-stationary, we use the following augmented Dickey-Fuller regression to test the null hypothesis that the price process is non-stationary:

$$\Delta P_t = \theta + \eta P_{t-1} + \zeta_t t + \sum_{i=1}^{I} \zeta_i \Delta P_{t-i} + \varepsilon_t \tag{21}$$

where $\Delta P_t = P_t - P_{t-1}$, θ is a constant, ζ_t is the coefficient on a time trend, and I is the lag order of the autoregressive process. A unit root test is then carried out under the null hypothesis $\eta = 0$ against the alternative hypothesis of $\eta < 0$. The results are reported in Table 3. The tests fail to reject the null hypothesis of non-stationarity. Therefore, we can assume that cotton price process follows a geometric Brownian motion process with an average growth rate (drift) α_P and a standard deviation σ_P. Based on the historical price data we have, We estimate α_P to be -0.01 and σ_P to be 0.20. Using 2012 as our base year, we forecast future cotton prices for a 25-yr period. These predicted prices then are used to forecast the discounted revenue differential V_T, if adoption were to be undertaken at time $T = 1, ..., 25$ for the HV and CC cover crop options under both conventional till and no till production systems.

For each of the cover crop adoption options, we estimate the growth rate α_v and standard deviation σ_v to characterize the stochastic process followed by V_T. Since V_T is non-stationary and follows a geometric Brownian motion (see Eq.(3)), it can be rewritten as:

$$\frac{dV}{V} = \alpha_v dt + \sigma_v dz \tag{22}$$

Purvis et al. (1995) use a Taylor series expansion to show that:

$$\frac{dV}{V} = \frac{\Delta V/\Delta t}{V} = \frac{1}{V} \times \frac{\Delta V}{\Delta t} = \frac{\Delta \ln(V)}{\Delta t} \tag{23}$$

By definition,

$$\Delta \ln(V_j) = \ln(V_t) - \ln(V_{t-1}) \tag{24}$$

where j denotes the size of the sample over which this difference is calculated.

In Eq.(24), the difference between the natural logarithms of V_t and of V_{t-1} gives a discrete estimate of the change in the value of an investment opportunity, as occurring over an increment of a Geometric Brownian motion process. Hence, the trend (α_v) of the Geometric Brownian motion process is estimated by:

$$\alpha_v \approx \frac{1}{N}\sum_{j=1}^{N}[\Delta \ln(V_j)] \tag{25}$$

The variance is estimated by:

$$\sigma_V^2 \approx \frac{1}{N-1}\sum_{j=1}^{N}[\Delta \ln(V_j) - \alpha_v]^2 \tag{26}$$

where $E[(\ln(V_j) - \alpha_v)^2] \geq 0$.

These growth rates and variance statistics can be used to solve Eq.(13) and (17), and then to derive an optimal investment trigger which takes partial irreversibility and uncertainty into account (Purvis et al. (1995)).

4 Empirical Results

A real options approach is applied to investigate the decision to invest in long-run cover crop use in cotton production systems while taking into account the following: uncertainty (in yields and prices), flexibility regarding when to invest, and partial irreversibility due to sunk costs.

Table 4 shows the impacts of cover crop adoptions on per hectare revenue, N fertilizer costs and quasi-rent differential (V), assuming a discount rate of 10%. The revenue and fertilizer cost estimates presented in Table 4 are average of the discounted per hectare values for the first 5 years if adoption were to occur at $T = 0$ (i.e., immediate adoption). As mentioned in the previous section, two scenarios are examined: (1) where the cover crop

options are compared against a "control" treatment without cover crops and without N fertilization, and (2) where the cover crop options are compared against a "control" without cover crops, but with 33.6 kg ha^{-1} N application). We find that adoption of HV cover crop leads to an increase in yields and therefore an increase in total revenues in both scenario 1 and 2, although the extent of these values varies with different tillage systems. The adoption of CC cover crop improves cotton yields and leads to positive quasi-rents for CT and NT in scenario 1, but the revenue and quasi-rents are negative when adopting it under NT in scenario 2, showing that it's not advisable to adopt CC cover crop at any time under NT in scenario 2.

The main results of our real options analysis are presented in Table 5 (where the optimal adoption trigger point (i.e., the expected net return that needs to be reached to prompt investment) and the timing of adoption are presented. Under the real options framework, the annual expected quasi-rent differentials of cover crop adoption have to be $\frac{\beta}{\beta-1}$ times the corresponding annual sunk cost. Under Scenario 1, the annual expected quasi-rent differentials from adopting the HV cover crop have to be 2.36 times and 2.19 times the annual sunk costs under conventional till and no till farming, respectively. On the other hand, the annual expected quasi-rent differential from adopting the CC cover crop has to be 1.81 times and 2.56 times the annual sunk costs under conventional till and no till farming, respectively. These figures suggest that expected returns that trigger adoption are relatively higher for HV than for CC. For Scenario 2, the annual expected quasi-rent differentials for HV have to be 2.33 times and 4.31 times higher than the annual sunk costs under conventional till and no till, respectively. Thus, when comparing a control treatment without cover crop and with 33.6 kg ha^{-1} N application), expected returns for cotton with HV needs to be higher in no-till systems (relative to conventional till) to trigger adoption.

Figures 1 to 7 show the time paths for $F(V)$ and $V - I$ under each scenario investigated. We begin each set of paths in 2012. When adopting cover crops, farms get the expected annual quasi-rent differential V, but at the same time gives up the opportunity to wait

to adopt in the future, which is valued at $F(V)$. Thus, its gain, net of the opportunity cost of adoption, is $V - F(V)$. The critical threshold value V^* is therefore where this net gain equals the sunk cost of adoption, I. Equivalently, we could also write the equation as $V^* = F(V) + I$, setting the value of cover crop adoption equal to the full cost of making this adoption investment.

Figure 1 presents the time paths of $F(V)$ and $V - I$ for hairy vetch adoption under conventional tillage. Since $V - I > 0$, the standard NPV rule would call for adoption immediately. However, $F(V) > V - I$, so farmers should wait rather than adopt now. In Figure 1, farmers need to wait approximately 16 years before V reaches critical value $V^* = \$549.61$ per hectare when adopting hairy vetch cover crop under conventional tillage system. This waiting time can vary considerably from one path to the next. In the path shown in Figure 2 for example, farmers must wait much longer — more than 25 years- before V reaches the critical value of \$345.88 per hectare for crimson clover adoption under conventional tillage farming. However, Figure 4 shows that it only takes 5 years to reach the critical value of \$400.076 per hectare for crimson clover adoption under no tillage farming.

Under scenario 2, we compare the annual quasi-rent differential with hairy vetch and crimson clover vis-á-vis a control treatment without cover crops but with fertilization at 33.6 kg ha^{-1} N. This allows us to see whether long-run use of HV or CC can be a natural N fertilizer substitute. Figure 5 and 7 show that the expected annual quasi-rent differential would not reach the critical value in the next 25 years under conventional tillage for both cover crop options. As shown in Figure 6, farmers need to wait 20 years before V reaches threshold value of \$852.23 per hectare when adopting HV under no till farming system. This suggests that adopting hairy vetch or crimson clover alone may not provide enough natural N supplement that is comparable to the use of synthetic N fertilizers.

The empirical results show that under an assumption of a 10% discount rate, the optimal delay in cover crop adoption for cotton production ranges from 5 to 20 years. In addition, results from the real options analysis suggest that farmers have to wait longer to adopt cover

crops under a conventional till farming system as compared to the no-till system. This is likely because the sunk cost of applying cover crops in a conventional till system is higher than in a no-till system. Hence, the real options approach indicate that it may be optimal to wait to adopt cover crops, rather than adopt immediately (as suggested by the NPV rule), especially when there is yield and price uncertainty involved.

Our analysis shows that despite the positive environmental impacts of cover crops on soil properties and productivity, there is lack of incentives for farmers to adopt cover crops immediately because of the sunk investment costs and uncertainty in economic returns. In recent years, there has been conservation programs offered at many levels, e.g., federal, state or county. Farmers can receive cost-share or subsidy payments to implement various conservation practices. Subsidy programs may be very important for promoting cover-crop adoption (Bergtold et al. (2017)). Therefore, we did a sensitivity analysis to examine how the trigger values and optimal timing decisions change if farmers were provided with a subsidy that can cover 30% of the total fixed costs of cover crop investment. As shown in Table 6, if a 30% subsidy was provided, there is a significant decrease in trigger point values and waiting time to adopt for HV and CC cover crop under NT in scenario 1 (when comparing against a control without cover crops and without fertilizer application). More specifically, when receiving a 30% subsidy, it's optimal for farmers to adopt CC immediately and adopt HV in the second year under NT in scenario 1. Under our real options analysis, the subsidy required as a percentage of the total fixed costs of adoption to induce immediate adoption ranges from 25% to 31% for HV under NT in scenario 1. Much higher subsidy rates are needed to induce immediate adoption of HV and CC in scenario 2 (when comparing with a "control" without cover crops, but with 33.6 kg ha^{-1} N application). By taking irreversibility of investment and uncertainty in future's economic returns into account, our real options framework provides a better way to structure more cost-effective government subsidy rates, and therefore helping to remove a major investment barrier to cover crop adoption.

5 Conclusion

In this study, we utilize the real options framework to evaluate the decision to invest in the long-run use of winter cover crops in cotton production systems. Two types of cover crops — hairy vetch and crimson clover — are evaluated to assess how uncertainty (in yields and prices), partial irreversibility due to sunk costs, and flexibility in adoption timing affects the decision to invest in winter cover crops. According to conventional financial analysis methods (such as the commonly used NPV rule), it is profitable for farmers to adopt these cover crops immediately. However, our study finds that uncertainty, irreversibility, and timing flexibility play important roles in farmers' decisions regarding the possible adoption of winter cover crops. Under uncertain economic conditions with irreversibility of the sunk cost and flexibility of the decision making, farmers need to take into account the potential value of waiting before adopting. Based on our empirical results, the optimal strategy for cotton farmers is to postpone winter cover crop adoption and to maintain the option of adopting this agricultural practice in the future (if there are no subsidies aimed at encouraging immediate adoption). More specifically, it is preferable to delay adoption in cover crops for at least 5 years under no-till farming (without subsidies). Delays in adoption are longer under conventional till farming because of a higher sunk cost of adopting cover crops in this system.

Therefore, unless there is new information that can help reduce uncertainty in returns to cover crop use or there are new innovations and subsidies to reduce the sunk costs, the real options analysis suggest that its is unlikely that there are immediate economic incentives to increase cover crop adoption rates. This paper provides a potential rationale for the currently observed low adoption rates of cover crops in the US and provides some insights for policy making. Given the lack of private economic incentives to immediately adopt the cover crop soil health practice, there is likely a role for government subsidies in helping reduce the sunk costs involved and encouraging more immediate adoption of this practice. The investment triggers from the real options approach may be able to help structure subsidy magnitudes that can encourage more investments in cover crops. The positive environmental externalities

generated from long-term use of cover crops (e.g., reduced soil erosion, reduced N runoff, etc.) can also be used to justify subsidy payments to encourage earlier adoption.

Although our study provides important insights regarding the effects of uncertainty and partial irreversibility (of the sunk cost) on cover crop adoption decision, it is important to recognize some limitations in this study. First, the present study only focuses on cotton production in West Tennessee, and the data is from experimental field trial data rather than actual farmer data from cotton production. The agricultural landscape has a wide variety of environmental conditions and local climates, which can result in different levels of success when adopting cover crops and other soil health practices. Economic outcomes from cover crop adoption area also likely to vary depending on a number of factors (e.g., the cash crop, the cover crop species, farmers' management decisions, etc.). Thus, future studies may consider implementing the real option framework used in this study in other contexts (e.g., for other cash crops, other cover crop species, using real farm production data, expanding the study area to other states or other countries). Second, we are assuming risk neutrality in our study (i.e., straightforward profit-maximization). Future studies can consider incorporating risk aversion in the real options framework to further analyze how farmers' optimal adoption decision change under varying levels of risk aversion. Lastly, having data for soil quality (i.e., soil organic matter) would allow us to more accurately estimate the long-run effects of cover crops on yields, and therefore discuss optimal adoption timing decisions under different soil conditions. Since we do not have access to soil quality data in our empirical setting, we leave this topic for future research.

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Table 1: Parameter estimates of the cotton yield response function to fertilizer N and time t by cover crop and tillage system.

	Conventional till			No-till		
Parameter	No cover crop	Hairy vetch	Crimson clover	No cover crop	Hairy vetch	Crimson clover
Intercept (β_0)	1279.024**	1434.245**	1505.533**	1114.173**	1273.774**	1231.545**
t (β_1)	-134.739**	-155.159**	-171.556**	-147.114**	-138.940**	-147.513**
t^2 (β_2)	8.437**	10.378**	11.253**	10.087**	10.475**	11.805**
t^3 (β_3)	-0.145**	-0.179**	-0.199**	-0.184**	-0.197**	-0.237**
N (β_4)	2.656**	1.887	-3.228**	6.627**	1.270	1.385
N^2 (β_5)	-0.027**	-0.031**	0.016	-0.055**	-0.033**	-0.017
$N \times t$ (β_6)	0.185**	0.107**	0.181**	0.163**	0.117**	0.072*
R^2	0.288	0.327	0.308	0.422	0.338	0.303

* Significant at 5% level.
** Significant at 1% level.

Table 2: Total sunk costs of adopting cover crops

	Conventional Till ($ ha^{-1})		No Till ($ ha^{-1})	
	Hairy Vetch	Crimson Clover	Hairy Vetch	Crimson Clover
Sunk Costs				
Seeds[a]	100.98	59.5	100.98	59.5
Machinery and labor costs[b]	38.73	38.73	49.39	49.39
Termination	93.17	93.17	47.45	47.45
Total sunk costs	232.88	191.4	197.82	156.34

[a] Cover crop seed prices were adjusted to 2012 dollars using the Implicit Gross Domestic Product Price Deflator (U.S. Bureau of Economic Analysis. (2019).

[b] Management labor costs are \$15 ha^{-1} for CT and NT. Machinery costs are \$23.73 ha^{-1} for CT, and \$ 34.39 ha^{-1} for NT.

Table 3: Dickey-Fuller test for non-stationarity of the price process

	Unrestricted model	Restricted model
θ	1.029 (2.80)	0.171 (1.03)
η	-0.010 (-2.59)	
ζ_t	-0.188 (-2.76)	-0.059 (-1.22)
ζ_1	-0.112 (-0.98)	-0.142 (-1.20)
ζ_2	-0.0251 (-0.22)	-0.028 (-0.24)
ζ_3	-0.051 (-0.46)	-0.058 (-0.50)
ζ_4	0.093 (0.89)	0.075 (-0.69)
N	79	79
t-statistic (critical values at 90 and 95% significance level)	2.76 (3.16, 3.47)	1.22 (2.59, 2.91)

Table 4: Average annual revenue gains, fertilizer costs and quasi-rents with adoption of cover crops[a]

Tillage system	Revenue ($ ha^{-1})					N fertilizer costs ($ ha^{-1})					Quasi-rent ($ ha^{-1})[b]	
	No cover crop	Cover Crop		Change in revenue		No cover crop	Cover Crop		Change in fertilizer costs			
		HV	CC	HV	CC		HV	CC	HV	CC	HV	CC
Scenario 1												
Conventional till	1957.07	2183.57	2244.47	226.50	287.40	0	0	0	0	0	226.50	287.40
No-till	1586.93	1961.71	1851.71	374.78	264.78	0	0	0	0	0	374.78	264.78
Scenario 2												
Conventional till	2112.03	2183.57	2244.47	71.54	132.44	36.72	0	0	-36.72	-36.72	108.26	169.16
No-till	1942.55	1961.71	1851.71	19.16	-90.84	36.72	0	0	-36.72	-36.72	55.88	-54.12

[a] Simulations done assuming a discount rate of 10%. Revenue and N fertilizer costs are average of the discounted per hectare values for the first 5 years if adoption were to occur at $T = 0$ (i.e., immediate adoption).

[b] Quasi-rent is equal to the difference between change in revenue and change in N fertilizer costs due to cover crop adoption.

Table 5: Optimal adoption decision for each cover crop option[a]

	$\frac{\beta}{\beta-1}$		Trigger point ($ ha^{-1})		Optimal timing of adoption (years)	
	CT	NT	CT	NT	CT	NT
Scenario 1						
Hairy Vetch	2.36	2.19	549.61	432.58	16	14
Crimson Clover	1.81	2.56	345.88	400.076	_ [b]	5
Scenario 2						
Hairy Vetch	2.33	4.31	542.38	852.23	_[b]	20
Crimson Clover	2.12	_[c]	404.98	_[c]	_[b]	_[c]

[a] Assuming a discount rate of 10%.
[b] Adoption is not profitable in the next 25 years.
[c] The estimated quasi-rent for crimson clover adoption is negative, so it's not advisable to adopt crimson clover at any time under NT in scenario 2.

Table 6: Optimal adoption decision for each cover crop option with 30% subsidy and subsidy requirements for immediate adoption[a]

	$\frac{\beta}{\beta-1}$		Trigger point ($ ha^{-1})		Optimal timing of adoption (years)		Subsidy requirement (%)	
	CT	NT	CT	NT	CT	NT	CT	NT
Scenario 1								
Hairy Vetch	2.36	2.19	384.73	302.81	2	2	35.02	31.01
Crimson Clover	1.81	2.56	242.11	280.05	_[b]	1	71.9	25.1
Scenario 2								
Hairy Vetch	2.33	4.31	379.67	596.56	23	17	62.5	72.3
Crimson Clover	2.12	_[c]	283.49	_[c]	_[b]	_[c]	59.3	_[c]

[a] Percentage of the total fixed costs reported in Table 2.
[b] Adoption is not profitable in the next 25 years.
[c] The estimated quasi-rent for crimson clover adoption is negative, so it's not advisable to adopt crimson clover at any time under NT in scenario 2.

Figures

Figure 1:Path of F(V) and V-I for Hairy Vetch adoption under Conventional Till: Scenario 1

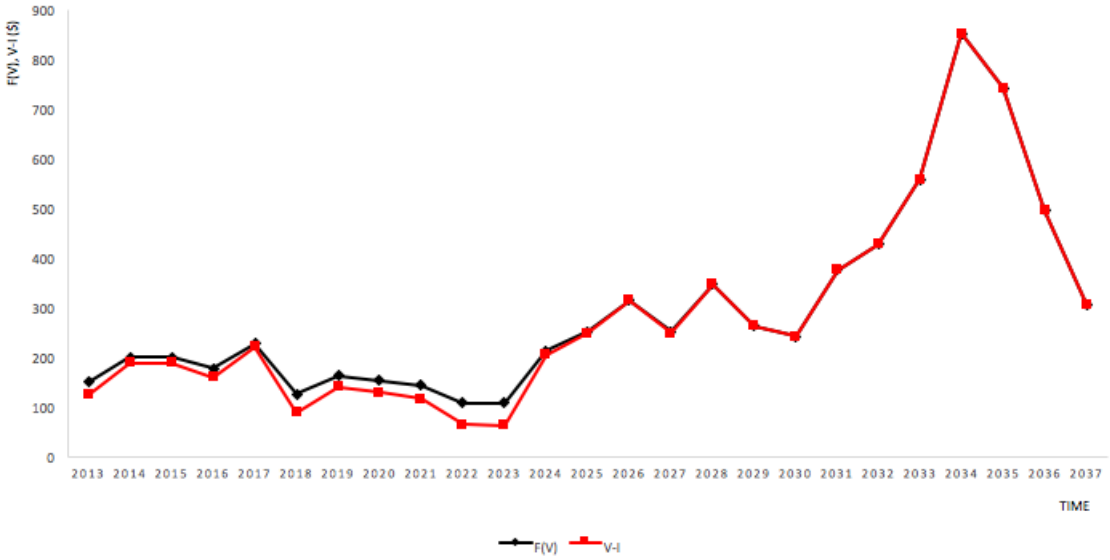

Figure 2: Path of F(V) and V-I for Crimson Clover adoption under Conventional Till: Scenario 1

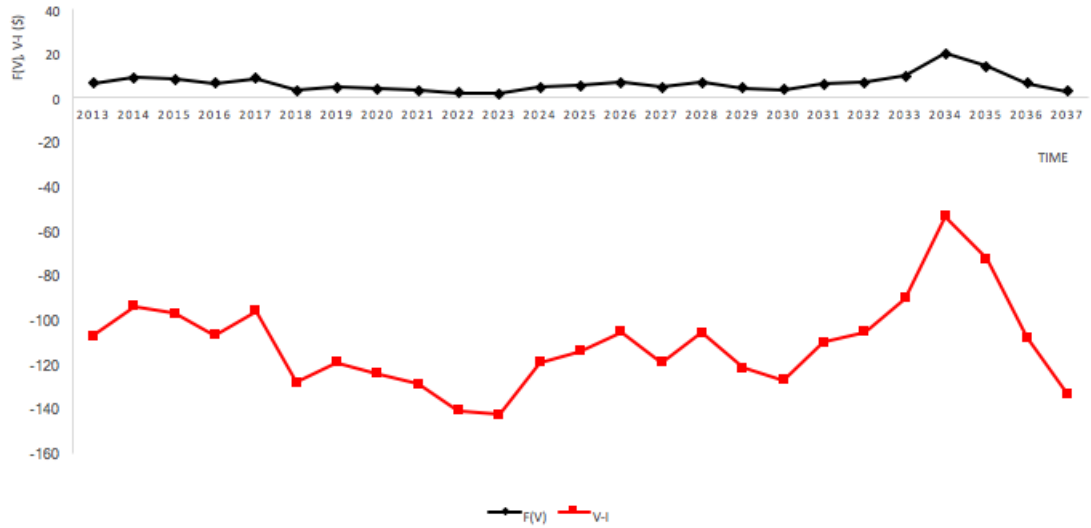

Figure 3: Path of F(V) and V-I for Hairy Vetch adoption under No Till: Scenario 1

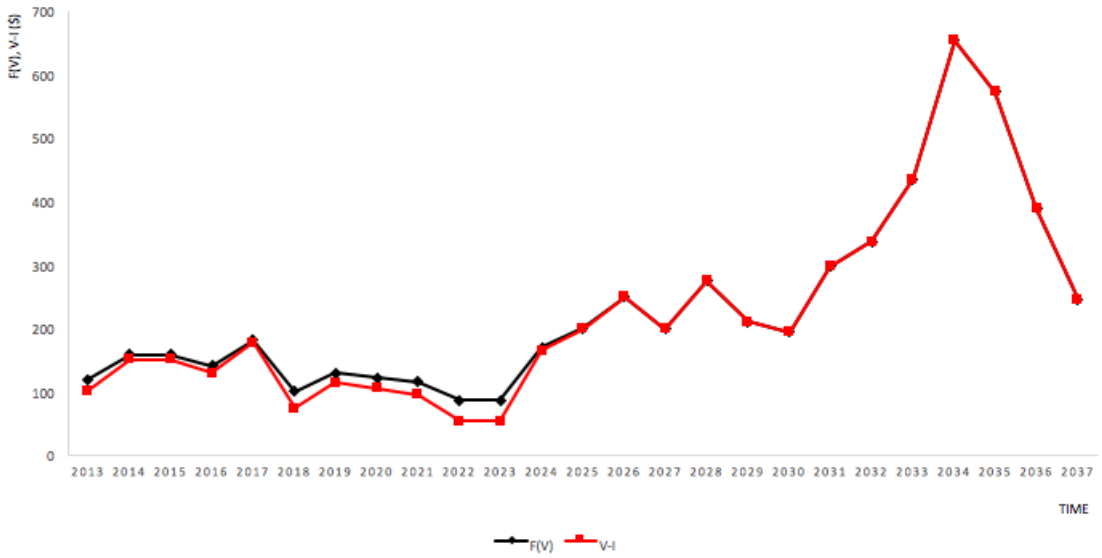

Figure 4: Path of F(V) and V-I for Crimson Clover adoption under No Till: Scenario 1

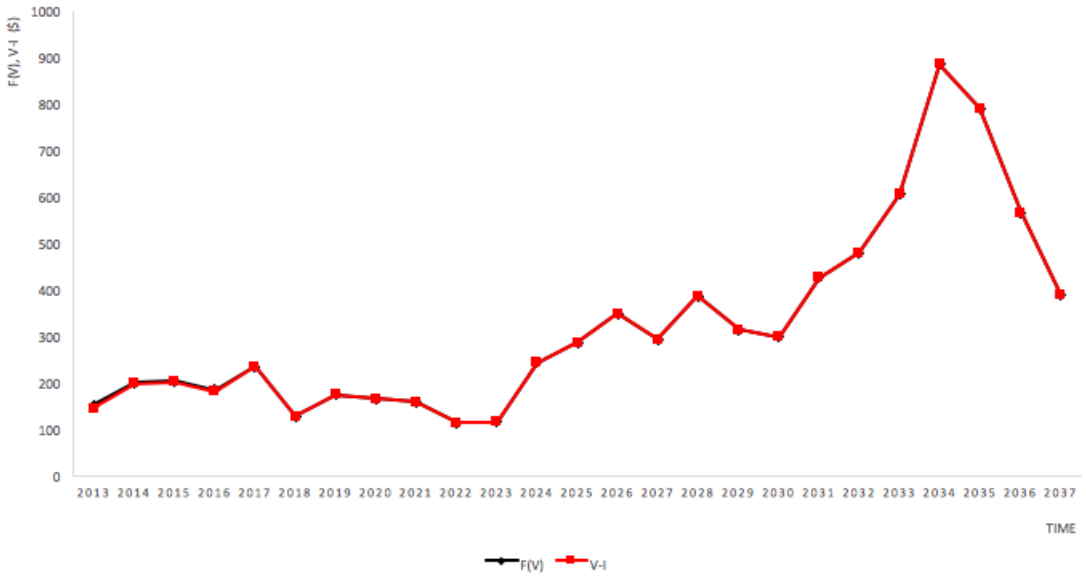

Figure 5: Path of F(V) and V-I for Hairy Vetch adoption under Conventional Till: Scenario 2

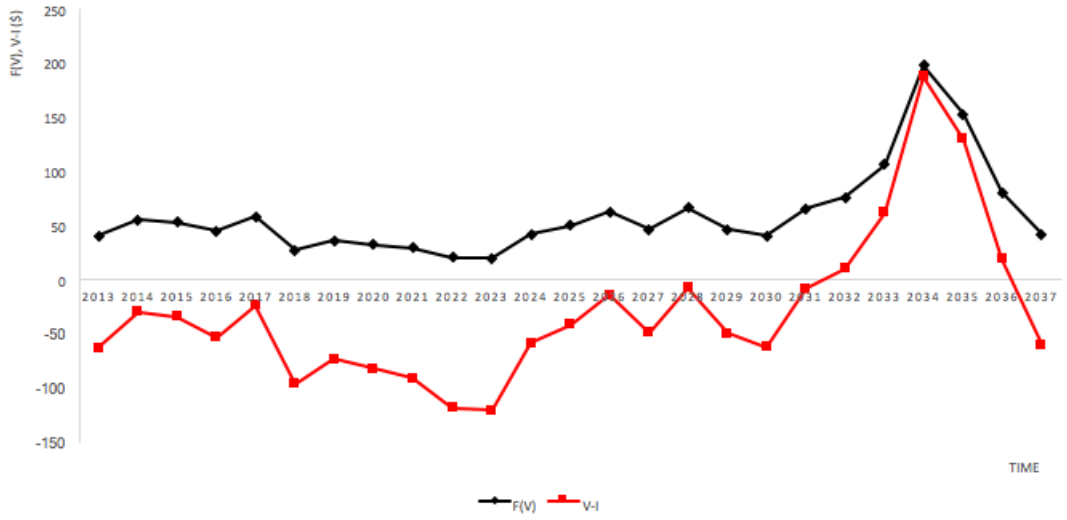

Figure 6: Path of F(V) and V-I for Hairy Vetch adoption under No Till: Scenario 2

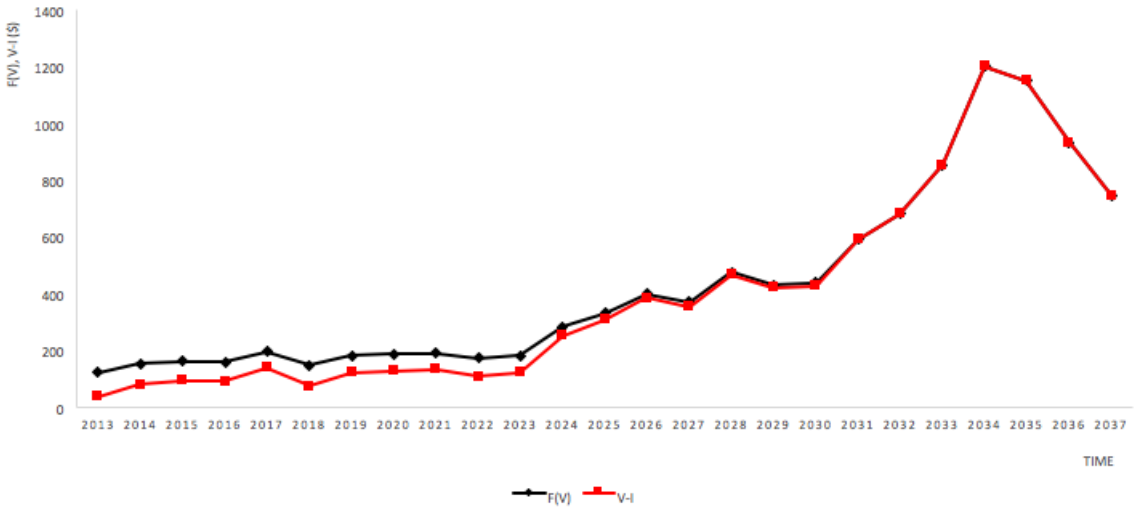
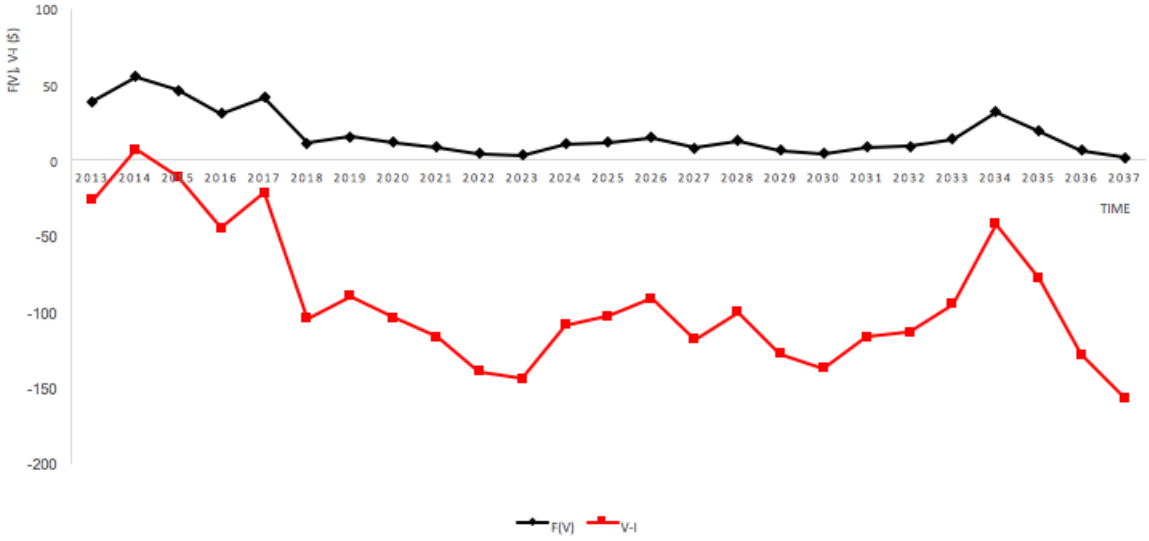
Figure 7: Path of F(V) and V-I for Crimson Clover adoption under Conventional Till: Scenario 2