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Rank-Ordered Analysis of Consumer Preferences for the Attributes of a Value-Added Biofuel Co-Product

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Abstract: Biochar is a co-product of the production of advanced biofuels that sequesters carbon when used as a soil amendment. Gardening consumers are a potential market for biochar and their purchase of biochar-amended products could provide biofuel producers with an additional revenue stream. To better understand this opportunity, preferences for the attributes of potting soils amended with biochar were elicited using a best-worst scaling experiment administered in a survey of 880 Tennessee households. The attributes analyzed were whether the biochar was produced in Tennessee, certified as biobased, a coproduct of biofuel production, and produced from food waste, wood waste, agricultural by-product, or a non-food energy crop feedstock. The effects of consumer demographics and attitudes on preferences for the biochar attributes were also estimated. We tested the independence of irrelevant alternative assumption using a structured covariance matrix designed specifically to the survey's structure. The results suggest that the attributes most likely to influence favorably consumers are production from agricultural by-product or wood waste feedstock. On the other hand, the attributes least likely to entice consumers are biochar produced in Tennessee or produced as a co-product of renewable fuel.

Keywords: biochar; best and worst scaling; IIA assumption; alternative specific rank ordered probit

1. Introduction

The Renewable Fuel Standard (RFS), introduced by the Energy Policy Act of 2005 and expanded by the Energy Independence and Security Act of 2007, commits the United States (U.S.) to increasing use of advanced biofuels for transportation through 2022. Advanced, or 'second generation' biofuels are produced with feedstock materials such as agricultural crop residues, food waste, and dedicated energy crops like miscanthus (*Miscanthus* spp.), switchgrass (*Panicum virgatum*), and woody biomass. These materials do not directly compete with food supply systems. The RFS requires the use of 36 billion gallons of renewable transportation fuel by 2022, with advanced biofuels accounting for 21 billion of those gallons. However, limited production of advanced biofuels makes it unlikely that either the 21 or 36 billion gallon targets will be met [1]. Advanced biofuel production has been hindered by a number of factors including investment risks, uncertainty in feedstock production and distribution, the availability of low-cost energy substitutes such as natural gas, and limited demand for biofuel co-products [2].

Co-products of biofuel production could increase the overall profitability of biofuel production and improve the growth potential of the biofuels industry. Furthermore, biofuel co-products add

value to economies through forward linkages to the production of goods such as food containers and wrapping, cosmetics, and household cleaning products [3]. Studies in Italy evaluated the use of olive oil production co-product as a renewable fuel [4,5]. Research in India on the sugar industry suggests that co-product from processing can be used to generate bio-electricity and bio-ethanol [6]. Other examples include the production of carbon dioxide (for industrial and medical use) and distiller's dried grains (a livestock feed supplement), both of which are co-products that add value to ethanol produced with corn.

Previous research focuses on consumer preferences for and attitudes towards biobased products. Several studies have focused on consumer knowledge of and perceptions about biobased products, including attributes extrinsic biobased content. Kainz et al. (2013) found that German consumers maintained positive views about bioplastics [7]. German consumers most commonly associated bioplastics with renewable resources and biodegradability. Fewer consumers believed that bioplastics contributed to environmental sustainability. Sijtsema et al. (2016) examined consumer perceptions about biobased products across the Czech Republic, Denmark, Italy, Germany, and the Netherlands [8]. Their results suggested that many respondents were unfamiliar with the term 'biobased'. However, consumers did associate 'biobased' with natural or environmentally friendly products and preferred them to conventional products. Sijtsema et al. reported that some consumers were concerned about the characteristics of the bioproducts offered with respect to functionality, aesthetics, and biodegradability. Consumers also exhibited some mistrust of biobased products with respect to purported characteristics of biodegradability and sustainability. Arjunan et al. (2010) proposed that key aspects of consumer interest in bioplastic development are the renewability of feedstock sources, products recyclability, and biodegradability [9]. This paper adds to the existing research on consumer preferences for biobased products by focusing specifically on biochar resulting from the production of bioenergy from various feedstock sources.

Biochar is a co-product of advanced biofuels produced by pyrolysis, gasification, or other thermic processes that use biomass or other biomaterials as a primary feedstock [10]. Biochar is a fine-grained, highly porous charcoal-like substance produced by heating biomass in the absence of oxygen. Biochar can be processed further to make carbon fiber composites, filters, or used directly as a soil amendment for row crop agriculture or by the greenhouse industry. There are no industrial patents for biochar; however, the thermolytic technologies producing biochar are typically patented. The addition of biochar to soils increases soil porosity and water retention capacity and sequesters carbon when used as a soil amendment [11].

Home gardening products are another potential value-added market for biochar. For example, biochar could be mixed with potting soil and sold by retail outlets that cater to home and lawn garden markets. In addition to enhancing the soil with potentially yield-increasing characteristics, the addition of biochar has the potential to reduce the need for inputs by increasing soil water holding capacity and nutrient availability. The addition of biochar also sequesters carbon. Thus, biochar-supplemented soil amendments may appeal to consumers with preferences for "environmentally friendly" home gardening products. The opportunity to support advanced biofuel production through the purchase of a co-product may also motivate some consumers. Prior research has identified segments of home gardeners interested in environmentally friendly products [3,10] Thus, consumer interest in products labeled as 'environmentally friendly', 'carbon-neutral', 'carbon offsetting', or 'green' suggests there is an opportunity to develop niche markets for biochar enhanced soil amendments.

The size and trajectory of the market for home gardening products suggests these niche markets could represent a meaningful destination for an advanced biofuel biochar co-product. Retail sales in the home gardening market have grown from \$21.8 billion in 2009 to \$32.6 billion in 2018 (U.S. Census Bureau, 2019). Average household expenditure on lawn care and gardening supplies was \$503 in 2017, up from \$363 in 2009 (National Gardening Association, 2018). The global market for potting soil alone is expected to increase by 2.8 percent to US \$1.8 billion by 2024, with the US capturing 29 percent of the market [12].

Using the results of a contingent valuation exercise in an online survey, Thomas et al. (2019) found that many Tennessee home gardeners were willing to pay a premium for a potting mix supplemented with biochar [13]. They also found that willingness to pay the premium was greater among younger respondents, those who spent more on gardening supplies, and those who were more concerned about the environment and the development of the biofuel industry. Building on the work of Thomas et al., this research estimates consumer preferences for specific biochar attributes. The study uses the results of a best-worst scaling experiment [14–16]—the one that was included in the same online survey of Tennessee home gardeners conducted by Thomas et al. 2019 [13]—to determine relative consumer preferences for four biochar attributes—bio-based certification, status as a co-product of renewable biofuel production, feedstock source, and geographic origin—and how these preferences vary across consumer demographics. Understanding consumer preferences for these attributes and how these preferences are related to demographic variables provides insight into the market potential for biochar-supplemented soil amendment, and possible target audiences for these products.

The objectives of this research are twofold. First, we aim to ascertain which of the four biochar attributes (certification, biomaterial source, renewable fuel co-product, and origin of production) resonate with potential consumers of biochar-supplemented soil amendments. Second, we measure how the level of salience varies across consumer demographic characteristics and attitudes.

Best-worst scaling (BWS) is a method to discern consumer preferences for features or qualities that frame referendums, products, or other goods. The strength of BWS is that the cognitive burden respondents experience during more complicated choice set designs (for example, conjoint analyses) may be reduced [17]. In other words, respondents' errors introduced by scaling bias are minimized because the presentation of BWS questions is comparatively easy to follow and answer. In this exercise, consumers who regularly purchased home gardening supplies were asked to rank the attributes of a generic potting soil mix with biochar in a hypothetical choice experiment. Respondent rankings of these attributes were conditioned based on demographic variables including age, gender, and income, and on attitudes toward home gardening, renewable energy, and the environment.

The empirical contribution of this paper addresses conceptual and computational challenges that can arise when BWS data is analyzed as discrete choices made by consumers. Rank ordered logit (ROL) regression is commonly used to regress best-worst rankings of product attributes conditioned on respondent characteristics. However, ROL analysis of BWS data assumes the independence of irrelevant alternatives (IIA). The IIA assumption maintains that, when faced with a set of alternatives, respondents are able to make pairwise comparisons among alternatives such that the pair under consideration is unaffected by the characteristics of other attributes [18]. We formulate an empirical test of the IIA hypothesis among the attributes characterizing the potting soil/biochar product. Failing to reject the null hypothesis of IIA suggests that the ROL is suitable for analyzing the scaling data. We propose a re-parameterization of the ROL as an alternative-specific rank ordered probit regression (ASROP) subject to rejection of the IIA hypothesis. The specific structure of the BWS data and the survey design used here requires restrictions on the correlations between best/worst alternatives to achieve model identification.

2. Data

A sample of 880 Tennessee residents aged 18 or older who self-identified as indoor or outdoor gardeners was solicited by the Qualtrics@online hosting service. A pretest survey of 108 respondents was conducted in June 2018. The remaining 772 respondents answered a revised survey in July 2018. There were 768 observations available for the BWS analysis after removing records with missing or incomplete responses.

The survey collected information on respondent age, gender, education, residential location, household income, and political orientation. The average age of respondents was 44 (Table 1). Most of the respondents were female (80 percent). Forty-one of the respondents had a college degree. Likewise, 39 percent reported their political orientation as conservative. Economically, socially, and culturally,

Tennessee is divided into three “grand divisions: east, middle, and west [19]. Twenty percent of respondents lived in west Tennessee, 42 percent in the middle of the state, and 38 percent in east Tennessee. Respondents reported their household’s 2017 income in one of twelve different ranges. The mean level of self-reported income was \$80,000 to \$100,000 per year. Finally, respondents were asked to report how frequently they purchased potting mix in a year and provide five response options (less than one, one, two, three, and four or more times). On average, respondents purchased potting soil between two and three times per year. Our sample of Tennessee households is similar to the population of U.S. gardeners. A 2014 survey conducted by the National Gardening Association reported that the average U.S. gardener was female, 45 years or older, and had a college degree or at least some college education [20].

Table 1. Definitions and Descriptive Statistics: Demographic and Factor Variables.

Variable	Description	Obs.	Mean	Std. Dev.	Min	Max
Demographic						
Age	Respondent age	768	44.07	14.90	18	79
Female	1 if respondent is female, 0 otherwise	768	0.80	0.40	0	1
College	1 if respondent has college degree, 0 otherwise	768	0.41	0.49	0	1
Urbanization	Nature of community in which respondent resides, 1=rural; 2=small town, 3=suburb, and 4=urban	768	2.26	1.04	1	4
Conservative	1 if respondents’ political orientation is conservative, 0 otherwise	768	0.39	0.49	0	1
East	1 if respondent resides in East Tennessee, 0 otherwise (base is West Tennessee)	768	0.38	0.49	0	1
Middle	1 if respondent resides in Middle Tennessee, 0 otherwise (base is West Tennessee)	768	0.42	0.49	0	1
Income	Household’s income before taxes for a year measured by 12 categories; 1=less than \$20,000, 2=\$20,000-\$39,999, 3=\$40,000-\$59,999, 4=\$60,000-\$79,999, 5=\$80,000-\$99,999, 6=\$100,000-\$119,999, 7=\$120,000-\$139,999, 8=\$140,000-\$159,999, 9=\$160,000-\$179,999, 10=\$180,000-\$199,999, 11=\$200,000 or greater, 12=prefer not to disclose	768	4.39	2.44	1	12
Frequency	1 if purchase potting mix less than 1 time per year; 2=1 time, 3=2 times, 4=3 times, 5=4 times or more times	768	3.32	1.13	1	5
Factor Score						
Gardening Product Quality	Factor score based on respondent attitudes toward gardening and gardening products	768	0.00	0.89	−5.41	1.61
Enthusiast Gardening	Factor score based on respondent attitudes about gardening	768	0.00	0.89	−3.93	2.31
Climate Change	Factor score based on respondent attitudes about climate change	768	0.00	0.91	−2.85	1.78

Respondents were asked to rank four biochar attributes in a hypothetical potting soil mix in a series of eight BWS scaling questions where the levels of the attributes varied from one question to the next. Specifically, respondents were asked to indicate which of the four attributes was the “most

attractive” and which was the “least attractive”. Each of the four attributes are extrinsic characteristics in that they are associated with non-physical traits of the product [21]. Recognizing that respondent familiarity with these attributes might be limited, a series of screens providing information on biochar and the individual attributes (Figures 1 and 2) preceded the choice experiment. The first attribute (*Certified*) pertains to whether the biochar is certified as a 100 percent U.S. Department of Agriculture Biobased Product [22].

What is Biochar?



Biochar is a charcoal-like material that can be added to soil to promote plant growth and reduce the amount of water and fertilizer needed. Biochar can also help with carbon sequestration or the storage of carbon in soils to help mitigate climate change. Biochar is made by burning biomass, such as crop residues, wood wastes or other organic matter, in an oxygen-starved environment through a process known as pyrolysis.

Figure 1. Biochar Information Screen.

Biochar can be made in different ways from different processes and, as a result, have different characteristics. Differences in these characteristics could affect whether consumers would want to purchase products that contain biochar. We ask that you read the following information on biochar characteristics and, in the series of questions that follow, indicate how important these characteristics would be to your decision to purchase potting mix that contains biochar.

(a)

Percent Biobased Content and USDA Certified Biobased Labeling

Biobased content is how much “new” or recent organic carbon is in an object or substance, compared to the amount of “old” organic carbon it contains. New organic carbon is carbon that comes from plants and other renewable agricultural, marine, and forestry materials, while old organic carbon comes from fossil fuels. USDA certifies biobased products under the USDA Certified Biobased labeling program.



A tree is 100% biobased



Coal is 0% biobased



The **USDA Certified Biobased Product** label indicates the ratio of new to total organic carbon. To determine the ratio, the products must undergo testing by a third party using government-approved standards and testing methods. This is a voluntary labeling program.

(b)

Biochar Source

Biochar can be derived from a variety of sources, including sustainably sourced wood wastes, food wastes, agricultural wastes, or non-food crops grown for energy production.



(c)

Figure 2. Cont.

Biochar As a Co-Product of the Production of Advanced Biofuel

One way that biochar can be produced is as a co-product of the production of advanced biofuels. Advanced biofuels are those that can be produced from woody crops, wood waste, agricultural waste, and other sources that do not compete directly with food production. These biomass sources can be converted to Syngas or bio-oil that can then be upgraded to replace transportation fuels such as conventional diesel and gasoline. Since biochar can be produced as a co-product of advanced biofuel production, a viable market for biochar can help make biofuel production more cost-effective.

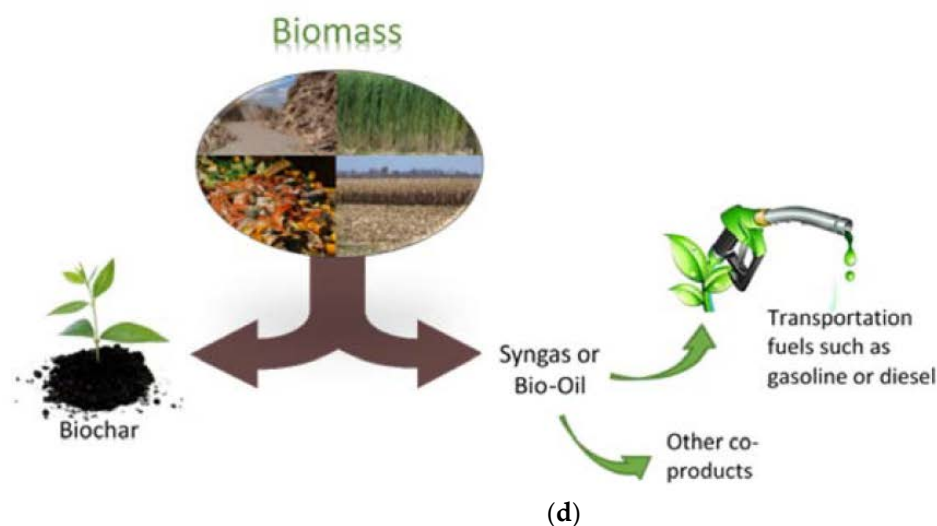


Figure 2. Biochar Attribute Information Screens. (a), information screen for content, (b) information screen for certification, (c) information screen for biochar source, (d) information screen for advanced fuel co-product.

The second attribute (*Biofuel*) indicated whether the biochar was a co-product of advanced biofuel production. This attribute also had two levels, yes or no. The information screen for this attribute indicated “a viable market for biochar can help make biofuel production more cost effective” (Figure 2). Thus, consumers who believe in the efficacy or value of advanced biofuels may be more inclined to purchase a product with biochar that is a co-product of advanced biofuel production as a means of contributing to the development of this industry.

The third product attribute (*Local*) indicated whether the biochar was produced in Tennessee. There were two levels for this attribute (yes or no) and no information screen.

The fourth attribute is the feedstock used to produce the biochar. This attribute included four levels: wood waste (S_W), food waste (S_F), agricultural by-products (S_A), and non-energy food crop (S_N). Each of the source levels may resonate differently among respondents and influence their ranking of the product’s features.

We hypothesize that consumers may be inclined to shy away from food crops, presuming they understand the implications for food prices. People may also respond negatively to food or agricultural waste out of contamination fears. Some consumers may react negatively to timber harvesting, even though the material used is from post-harvest wood waste. We do not expect that biomaterial origin (*Local*) will have too much of an influence relative to the other attributes if consumers do not anticipate biochar production to have localized benefits. While some consumer segments might view *Local* as a net positive (either because any local economic activity is good or they want to reduce energy use and emissions associated with transportation positively), we do not expect that this attribute would be comparatively more attractive than the other attributes. Because ‘biobased’ and ‘biofuel co-product’ are terms that may be too abstract or complex to generate consumer enthusiasm, we expected the source to have the most salience.

A balanced fractional design was used to generate the subset of alternatives for the eight tasks. In a balanced design, attribute levels appear with levels of other attributes equally often and levels

within attributes an equal number of times [23]. The balanced fractional design ensures that the main effect design is orthogonal, such that the correlation between alternatives is zero [24]. There were $2 \times 2 \times 2 \times 4 = 32$ possible combinations in the choice experiment's design space, with $J = 7$ product attributes (*Certification, Local, Biofuel, S_W, S_F, S_A, S_N*). The SAS macro % *mktex* (SAS, 2018) was used to generate four unique fractional designs by varying a random seed, resulting in four 8-task sets. The task sets were randomized across respondents, resulting in 20 versions of the survey. Respondents were randomly assigned to survey versions. Given the experimental design and the number of respondents, there were 24,576 observations used in the analysis, with 6144 unique cases.

Data coding for this analysis follows Louviere, Flynn, and Marley's (2015) BWS method [23]. For $t = 1, 2, \dots, 8$ trials (or tasks), respondent $i = 1, 2, \dots, n$ identified the best and worst attribute of the product after reading the following information screen (Figure 3) (An electronic version of the survey is available from the corresponding author. The distributions of best-worst rankings are in Appendix A):

Suppose you could select from potting mix with biochar where the source of the biochar or the way in which the biochar was made differs from one product to another. Please review the following biochar product characteristics and select the characteristic that you believe is most attractive and the one you believe is least attractive.

Most Attractive		Least Attractive
<input type="radio"/>	<i>The biochar IS NOT</i> 100% USDA CERTIFIED BIOBASED	<input type="radio"/>
<input type="radio"/>	<i>The biochar IS a CO-</i> PRODUCT OF RENEWABLE BIOFUEL	<input type="radio"/>
<input type="radio"/>	<i>The source of the</i> <i>biochar is WOOD</i> WASTE	<input type="radio"/>
<input type="radio"/>	<i>The biochar IS NOT</i> PRODUCED IN TENNESSEE	<input type="radio"/>

Figure 3. A typical best/worst task screen.

Factor Variables

Consumer views on environmental issues and climate change, their familiarity with renewable energy, their perceptions of, and enthusiasm for, gardening, and their opinions on the importance of gardening product attributes were elicited with 26 Likert-scaled questions (Table 2). We used factor analysis to group responses to the Likert-style questions into general categories. Factor analysis uses correlations between related variables to summarize groups of variables in terms of a limited number of latent random components [25]. The procedure uses principle components to assign variables to categories whose members are strongly correlated. Category partitions are identified by a common, latent factor that retains information on the heterogeneity of the variables included in the category. The resulting factors are orthogonal, thereby reducing collinearity problems that might arise if all variables were included in the regression as explanatory variables. Standardized factor loadings are interpretable as correlation coefficients. The number of factors was determined by inspecting the principle component eigenvalues. The number of factors retained was determined when the running sum of the principle component eigenvalues equaled 50 percent [26]. The resulting factors are included as covariates in the best/worst regressions.

Table 2. Definitions and Descriptive Statistics: Attitudinal Variables.

Attitudinal Statements	Obs.	Mean	Std.Dev.	Min	Max
Level of agreement with the following statements					
I enjoy spending time outside.	768	4.13	0.85	1	5
Gardening is a source of exercise for me.	768	3.89	1.12	1	5
Gardening is relaxing.	768	4.07	0.97	1	5
I enjoy residing in a property that is attractive.	768	4.10	0.73	1	5
I like to grow my own food.	768	3.88	1.11	1	5
I love growing flowers.	768	4.04	0.90	1	5
I believe growing plants helps the environment.	768	4.13	0.74	1	5
I like learning about plants.	768	4.17	0.91	1	5
Gardens can provide wildlife habitat.	768	4.08	0.93	1	5
Responses to this survey could cause potting mix manufacturers to change the characteristics of the mixes they sell.	768	2.18	1.15	1	5
Home gardeners can impact the environment with their gardening practices.	768	3.42	1.06	1	5
My personal actions do not have any significant effect on the environment.	768	3.81	0.97	1	5
Science and technology will come up with ways to solve environmental damage and pollution.	768	4.51	0.76	1	5
Most people are not willing to make sacrifices to protect the environment.	768	3.76	0.91	1	5
We have a responsibility to future generations to protect the environment.	768	4.26	0.82	1	5
Biofuels are important for meeting the nation's future energy needs.	768	4.01	1.13	1	5
Global climate change is occurring.	768	3.99	1.11	1	5
Climate change will lead to environmental and health problems in many parts of the world.	768	2.23	1.30	1	5
There is no urgent need to take measures to prevent climate change.	768	3.99	0.90	1	5
I do not have enough knowledge to make well-informed decisions on environmental issues.	768	2.82	1.20	1	5
How important is it for the gardening products you purchase to					
Be organic?	768	3.54	1.11	1	5
Have decreased need for water?	768	3.73	0.97	1	5
Have decreased need for fertilizers?	768	3.91	0.95	1	5
Have decreased need for pesticides?	768	4.30	0.89	1	5
Be native plant species?	768	3.63	0.98	1	5
Come in recyclable packaging or containers?	768	3.70	1.06	1	5

The Likert scale labels are 1 if the response is strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5=strongly agree.

Factor analysis reduced the 26 Likert scale questions to three groupings (Table 3). Uniqueness is an indicator of the importance of that variable to a factor. Variables with lower uniqueness values contribute more in terms of an explanatory component of a factor [25]. For the first factor, six variables had a factor loading with an absolute value above 50 percent. The variables included in this factor formed a cluster affiliated with love of gardening and appreciation for attractive landscapes. Thus, this factor is labeled as “Gardening Enthusiasts”. The second factor had four values with factor loadings above 50 percent, all related to placing higher importance on purchasing gardening products with reduced needs for water, fertilizer, and pesticides or that come in recyclable packaging. We labeled this second factor “Gardening Product Quality”. Four variables loaded on the third factor, all related to environmental issues. In particular, a greater belief that science and technology will “solve environmental damage and pollution”, biofuels are important for meeting the nation’s future energy needs, and climate change is occurring but will not lead to “environmental and health problems

in many parts of the world”. Thus, this factor, which is labeled the “Climate and Energy” factor, captures respondent belief that science and technology, including biofuels, will address our climate and environmental problems. These three factors were included as covariates in the best-worst regressions.

Table 3. Factor Analysis: Attitudinal Variables Related to Environment and Gardening.

Attitudinal Statements	Gardening Enthusiast	Gardening Product Quality	Climate and Energy	Uniqueness
Level of agreement with the following statements				
I enjoy spending time outside.	0.60	0.03	−0.02	0.64
Gardening is a source of exercise for me.	0.42	0.07	0.00	0.82
Gardening is relaxing.	0.52	0.09	0.04	0.72
I enjoy residing in a property that is attractive.	0.66	0.01	0.03	0.56
I like to grow my own food.	0.39	0.12	0.01	0.83
I love growing flowers.	0.53	0.07	0.04	0.71
I believe growing plants helps the environment.	0.65	0.01	−0.02	0.58
I like learning about plants.	0.58	0.04	0.06	0.66
Gardens can provide wildlife habitat.	0.42	0.05	0.08	0.81
Responses to this survey could cause potting mix manufacturers to change the characteristics of the mixes they sell.	0.08	−0.06	−0.44	0.80
Home gardeners can impact the environment with their gardening practices.	0.08	0.21	0.03	0.95
My personal actions do not have any significant effect on the environment.	0.15	0.11	0.15	0.94
Science and technology will come up with ways to solve environmental damage and pollution.	0.18	0.34	0.56	0.54
Most people are not willing to make sacrifices to protect the environment.	0.13	0.37	0.29	0.77
We have a responsibility to future generations to protect the environment.	0.19	0.41	0.42	0.62
Biofuels are important for meeting the nation’s future energy needs.	0.12	0.16	0.77	0.37
Global climate change is occurring.	0.12	0.17	0.78	0.34
Climate change will lead to environmental and health problems in many parts of the world.	0.03	0.02	−0.61	0.62
There is no urgent need to take measures to prevent climate change.	0.12	0.40	0.37	0.69
I do not have enough knowledge to make well-informed decisions on environmental issues.	0.02	−0.07	−0.26	0.93
How important is it for the gardening products you purchase to				
Be organic?	0.09	0.45	0.18	0.76
Have decreased need for water?	0.01	0.63	0.00	0.60
Have decreased need for fertilizers?	0.04	0.73	0.03	0.47
Have decreased need for pesticides?	0.09	0.61	0.13	0.60
Be native plant species?	0.02	0.49	0.08	0.75
Come in recyclable packaging or containers?	0.01	0.55	0.28	0.61

Note: Factor loadings larger than 0.5 in bold.

3. Methods and Procedures

The probability a consumer ranks the j th attribute as the product’s most attractive feature is modeled as an ordered sequence of conditional probabilities. Beggs et al. (1981) extended McFadden’s (1974) random utility framework to a rank ordered specification for estimating probabilities associated with preference rankings [27,28]. Allison and Christaks (1994) demonstrated how different parametrizations of the random utility model unify conditional logit, multinomial logit, and rank ordered logit methods to estimate choice probabilities [29]. We adopted Allison and Christaks’ approach, extending their estimation procedure to an alternative-specific rank ordered probit regression. This extension relaxes the assumption of independence between alternatives maintained by the rank ordered logit procedure.

The choice experiments required respondents to indicate which of the four attributes associated with the biochar amendment was most attractive (or “best”), and which option was least attractive (the “worst”) (Figure 3). The remaining two unchosen attributes were enumerated as ties. The linear additive random utility function used here characterizes the choice sets and tasks for each respondent as:

$$v_{ijt}^* = \sum_j c_{jt} \cdot \delta_j + \sum_j \sum_k \beta_{jk} \cdot c_{jt} \cdot x_{ik} + \epsilon_{ijt} \quad (1)$$

where v_{ijt}^* is the latent utility of the i th respondent from the t th task derived from attribute set $j \in \{C, T, B, S_W, S_F, S_A, S_N\}$, where k indexes respondent i 's demographic characteristics; c_{ijt} are alternative-specific variables equal to one when attribute j is included in the choice set; x are case-specific variables including respondent characteristics; δ and β are conformable parameter vectors; and ϵ_{ijt} is a random component of utility that is independently and identically distributed with an expected value of zero and a constant variance.

Utility is unobservable in practice. In the BWS format used here, a discrete (0, 1, 2) variable indicates the worst ($y_j = \text{worst}$), tied ($y_j = \text{tied}$), and best ($y_j = \text{best}$) features of the biochar product. Choice sets for this sequential process are consistent with the conditional logit model; thus observed rankings can be formulated as the product of independent probabilities of choosing “best” for an attribute from consecutively smaller subsets [23]. Allison and Christakis reformulated the rank ordered logit likelihood as a partial likelihood function to handle ties. These probabilities can be estimated as an ROL regression if the errors of equation 1 are independent and identically distributed and are from the Type I Extreme Value distribution [18].

3.1. Correlated Attributes and the IIA Assumption

The rank ordered logit specification maintains that the conditional distribution of utility derived from a choice set is independent of other choice sets. We verified this assumption with a likelihood ratio (LR) test. The null hypothesis of this test is that the error correlations between attributes are zero. The LR test compares a fully efficient model that includes covariances across all alternatives with a model that restricts covariates to zero. If the IIA assumption is maintained, then the coefficients of each model are not statistically different, meaning that the exclusion of one alternative does not affect the respondents' ranking of the best and worst qualities of the product.

If the evidence suggests the IIA assumption is violated, an alternative-specific rank ordered probit regression (ASROP) can be used to analyze ranked data instead of the ROL regression [30]. The ASROP estimator relaxes the IIA assumption by allowing correlations between each attribute in a symmetric, positive definite covariance matrix Ω that includes covariances across the $J = 7$ attributes. The ASROP covariance estimator is identified by 1) choosing an arbitrary attribute as a base category and 2) choosing another attribute for scale normalization. For example, selecting attribute C as the reference category set eliminates the first row and column of Ω . For scale normalization, and arbitrarily selecting attribute T (= origin) for normalization, the orthogonal matrix

$$\mathbf{M} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \quad (2)$$

restricts the variance of attribute T to 2, with unrestricted covariance terms with the remaining attributes. Lastly, the structure of the experimental design requires a third restriction on the covariance terms in Ω . According to the survey design, each choice set includes attributes (labeling, origin, material, and feedstock), where the first three attributes each have two levels and the source attribute has four levels; S_W , S_F , S_A and S_N . For any given best-worst screen seen by a respondent, only one of the four

feedstock attributes appears, while some level combination of attributes C , T , and B (each with two levels) always appears. This design means that the covariance between feedstock levels is zero, but each feedstock level may be correlated with attributes C , T , and B . After zeroing out the covariance terms between feedstock levels and declaring a reference category, pre- and post-multiplication of the augmented covariance structure by \mathbf{M} yields the required covariance matrix:

$$\epsilon_i \sim MVN(\mathbf{0}, \mathbf{M}\mathbf{\Omega}\mathbf{M}') = MVN \left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 & \omega_{TB} & \omega_{TSW} & \omega_{TSF} & \omega_{TSA} & \omega_{TSN} \\ \omega_{TB} & \omega_B^2 & \omega_{BSW} & \omega_{BSF} & \omega_{BSA} & \omega_{BSN} \\ \omega_{TSW} & \omega_{BSW} & \omega_{SW}^2 & 0 & 0 & 0 \\ \omega_{TSF} & \omega_{BSF} & 0 & \omega_{SF}^2 & \omega & \omega \\ \omega_{TSA} & \omega_{BA} & 0 & 0 & \omega_{SA}^2 & \omega \\ \omega_{TSN} & \omega_{BSN} & 0 & 0 & 0 & \omega_{SN}^2 \end{bmatrix} \right) \quad (3)$$

where MVN indicates the multivariate normal distribution and ω_{jk} the covariance terms of the ϵ_i error components.

We used simulated maximum likelihood to estimate the model parameters (δ , β , $\mathbf{M}\mathbf{\Omega}\mathbf{M}'$). The multivariate distribution was approximated with the GHK algorithm [31–34] included in STATA's *asroprobit* routine [24]. Covariance restrictions were imposed using the procedure's constraint option.

A Chi-square statistic was used to test the diagonality of the ASROP covariance matrix. Under the null hypothesis of IIA, the critical value of this joint test is 14.06 at the 1% level of significance (9 degrees of freedom). We conducted this test for each attribute to determine which product features cause violation of the IIA assumption. The critical Chi-square value for the individual tests is 9.24 for attributes C (certified biobased), T (origin), and B (renewable biofuel). For the feedstock attributes (S = wood waste, agricultural byproducts, food waste, and non-food energy crops), the critical Chi-square value is 4.61, with each test having two degrees of freedom.

3.2. Marginal Effects

The association between each attribute and respondent characteristic is measured with the marginal effects of the respondent's characteristics on the likelihood of categorizing a product feature as 'best' or 'worst'. The marginal effect of individual characteristics when an attribute is chosen as 'best' is

$$\frac{\partial \Pr(y_j = \text{best})}{\partial x_k} = \left[\Pr(y_j^* | y_{j-1}) \times \Pr(y_{j-1}^* | y_{j-2}) \right] \cdot \beta_{jk} \quad (4)$$

which can be calculated by a one unit change in the treated variable, given that the other variables are at their means. Standard errors of the marginal effects were estimated using the delta method [33].

4. Results

4.1. Consumer Perceptions

Respondents generally held favorable views of gardening and its benefits (Table 2). On average, respondents were ambiguous about whether their behavior or that of gardeners more generally is likely to have an effect on the environment (Table 2). This ambiguity could be a reflection of the spatial ambiguity of the term "the environment". Thus, some respondents may consider the potentially significant effect gardeners can have on the environment in their backyards, while others may consider the relatively insignificant environmental impact a single home gardener is likely to have on a broader geographic scale. In general, respondents believed that "we have a responsibility to future generations to protect the environment" and expressed a great deal of confidence in the ability of science and technology to "solve environmental damage and pollution". On balance, consumers believed climate change is "occurring" but expressed little urgency to "take measures to prevent climate change" or concern that climate change would "lead to environmental and health problems in many parts of the

world” (Table 2). One possible characterization of these responses in aggregate is that respondents seem willing to accept the fact of climate change but not the implications or responsibilities associated with climate change. Respondents generally regarded organic, native, decreased need for inputs, and recyclable packaging as somewhat important attributes of gardening activities and products.

4.2. Regression Results

The log-likelihood of the restricted ASROP probit model was $-12,726$. The ASROP unrestricted log-likelihood was $-12,716$ (Table 4). The joint test that the ASROP correlation matrix was diagonal was rejected at the 1% level of significance, leading us to reject the IIA null hypothesis. Rejection of the null was caused by the certification, origin, and renewable biofuel co-product attributes. We therefore report the ASROP results estimated with the unrestricted covariance matrix of equation 4. (The correlation values are in Appendix B).

Table 4. Log-likelihood Ratio Test for Independence of Irrelevant Alternatives Assumption.

Controlled Attribute	Chi-Square Statistic	Degrees of Freedom	Critical Value ($\alpha = 0.10$)
USDA certifies bio-based products	17.74 ***	5	9.24
Produced in Tennessee	17.73 ***	5	9.24
Renewable fuel co-product	13.00 **	5	9.24
Source: wood waste	4.99 *	2	4.61
Source: food waste	2.62	2	4.61
Source: Agricultural by-product	2.58	2	4.61
Source: nonfood energy	3.55	2	4.61
All attributes	18.80 **	9	14.68

*** = significant at $\alpha = 0.01$, ** = significant at $\alpha = 0.05$, * = significant at $\alpha = 0.1$.

4.3. Model Estimates and Marginal Effects

Origin, certification, and co-product status play an important role in preference rankings for biochar-amended potting mix, as does the biochar source (Table 5). Respondent purchasing frequency of potting mix, age, education level, political affiliation, and the attitudinal factor analysis variables are associated with one or more of the rankings of the biochar product attributes. Purchase frequency was negatively associated with both being produced in Tennessee and being a renewable biofuel co-product. Thus, respondents who purchased potting mix more frequently were less likely to consider biochar produced in Tennessee or as a co-product of renewable biofuel production to be an attractive feature than they were to consider 100% USDA certified biobased. Older respondents are more likely to consider sourcing biochar from either wood waste of nonfood energy crop feedstock as features that are more attractive. College educated respondents were more likely to consider being a renewable biofuel co-product to be an attractive attribute, while politically conservative respondents were more likely to consider biochar produced from wood waste to be an attractive attribute. The Gardening Enthusiast factor variable was positively associated with the agricultural by-product attribute, suggesting that respondents who were most enthusiastic about gardening also tended to be more enthusiastic about biochar sourced from agricultural by-products. The gardening Product Quality factor was positively associated with produced in Tennessee and sourced from nonfood energy crop feedstock, while the Climate Change factor variable was positively associated with all but produced in Tennessee. Gender, residential location, and income were uncorrelated with the rankings of the biochar attribute.

Table 5. Alternative-Specific Rank Ordered Probit Estimates.

Variable		Certified Bio-Based (B)	Produced in Tennessee (T)	Biofuel Co-Product (C)	Source:			
					Wood Waste	Food Waste	Ag. Co-Product	Nonfood Energy Crop
Attributes								
Yes	Estimate z-value	1.95 42.97 ***	1.28 31.63 ***	1.12 27.68 ***				
Variables								
Frequency	Estimate z-value		−0.05 −2.28 **	−0.05 2.21 **	−0.04 1.02	0.04 0.93	−0.06 1.53	0.01 0.17
Age	Estimate z-value		0.00 1.54	0.00 1.44	0.01 2.61 ***	0.00 0.67	0.01 1.61	0.01 2.52 **
Female	Estimate z-value		−0.01 −0.25	−0.05 −0.89	−0.05 −0.46	0.06 0.52	−0.13 −1.13	−0.05 −0.49
College	Estimate z-value		0.00 0.08	0.10 1.97 **	0.03 0.30	0.10 1.07	−0.01 −0.09	−0.04 −0.50
Urban	Estimate z-value		−0.02 −0.71	0.01 0.43	0.00 0.05	−0.04 −0.78	−0.03 −0.56	−0.03 −0.85
Conservative	Estimate z-value	Base Alternative	0.07 1.39	0.06 1.21	0.20 2.23 **	0.16 1.62	0.14 1.41	0.09 1.01
East Tennessee	Estimate z-value		0.04 0.66	−0.04 −0.67	0.01 0.12	−0.01 −0.04	−0.06 −0.48	−0.11 −0.97
Middle Tennessee	Estimate z-value		−0.00 −0.01	−0.05 −0.73	−0.04 −0.35	−0.10 −0.81	−0.20 −1.59	−0.03 −0.28
Income	Estimate z-value		−0.00 −0.17	0.01 0.47	0.00 0.11	0.01 0.76	0.02 0.89	0.01 0.84
Gardening Enthusiast	Estimate z-value		0.03 1.07	−0.01 −0.20	0.05 1.02	0.04 0.89	0.16 3.14 ***	0.02 0.50
Gardening Product Quality	Estimate z-value		0.06 2.41 **	0.03 0.97	0.04 0.78	0.08 1.60	0.08 1.54	0.08 1.71 *
Climate Change	Estimate z-value		−0.04 −1.48	0.06 2.17 **	0.09 1.96 **	0.13 2.44 **	0.13 2.32 **	0.10 2.04 **
Intercept	Estimate z-value		0.25 1.72 *	0.34 2.33 **	1.11 4.53 ***	1.12 4.13 ***	1.70 6.05 ***	0.88 3.60 ***

*** = significant at $\alpha = 0.01$, ** = significant at $\alpha = 0.05$, * = significant at $\alpha = 0.10$ (Shading indicates significant entries). Number of observations = 24576, Number of cases = 6144. Log-likelihood = −12716.

We estimated the marginal effects of respondent attributes on the biochar attribute rankings using Equation (5) (Table 6). Negative (positive) signs of the marginal effects correspond with an attribute deemed ‘worst’ (‘best’). We discuss marginal effects that were significant at the 10% level or lower. Respondents who purchased potting mix more frequently were more likely to rank having food waste as the biochar feedstock as the best attribute. Holding other variables constant, a one-level increase in frequency was associated with a 1.52% increase in the likelihood of ranking the food waste feedstock attribute as the best attribute. Older individuals were less likely to rank USDA bio-based certification as a desirable attribute. Other factors constant, a 10-year increase in age was associated with a −0.06% decrease in the probability a respondent ranked certification as the biochar-amended potting soil’s most attractive feature. Politically conservative respondents were 1.83% less likely to rank 100% USDA Certified Biobased as an attractive product trait. Interestingly, respondents expressing concern about climate change and the nation’s future energy needs were more likely to rank certification as a less attractive product trait. Likewise, gardening enthusiasts who expected that home garden products would decrease the use of fertilizers and water were also less likely to consider USDA certification attribute.

Table 6. Marginal Effects of Alternative-Specific Rank Ordered Probit Estimates.

Variable		Certified Bio-Based (B)	Origin: Produced in Tennessee (T)	Biofuel Co-Product (C)	Source: Wood Waste	Source: Food Waste	Source: Ag. Co-Product	Source: Nonfood Energy Crop
Frequency	Marginal effect	0.29%	−0.29%	−0.32%	−0.42%	1.52%	−1.28%	0.49%
	z-value	1.03	−1.50	−1.50	−0.56	1.75 *	−1.35	0.83
Age (per 10 years)	Marginal effect	−0.06%	−0.02%	−0.02%	0.08%	−0.06%	0.03%	0.05%
	z-value	−2.95 ***	−1.38	−1.39	1.36	−0.85	0.37	1.19
College	Marginal effect	−0.37%	−0.21%	0.88%	0.00%	2.03%	−1.04%	−1.30%
	z-value	−0.55	−0.45	1.71 *	0.00	0.98	−0.46	−0.90
Conser-vative	Marginal effect	−1.83%	−0.54%	−0.71%	1.90%	1.00%	0.64%	−0.55%
	z-value	−2.67 ***	−1.17	−1.38	1.05	0.48	0.28	−0.38
Gardening Enthusiast	Marginal effect	−0.85%	−0.29%	−0.72%	−0.23%	−0.34%	2.98%	−0.62%
	z-value	−2.45 **	−1.24	−2.74	−0.25	−0.32	2.57 **	−0.83
Gardening Product Quality	Marginal effect	−0.87%	−0.07%	−0.38%	−0.53%	0.63%	0.67%	0.40%
	z-value	−2.45 **	−0.28	−1.40	−0.57	0.57	0.55	0.53
Climate Change	Marginal effect	−1.31%	−1.35%	−0.31%	0.26%	1.14%	1.19%	0.28%
	z-value	−3.50 ***	−5.08 ***	−1.10	0.26	1.00	0.95	0.35
Probability attribute ranked as ‘best’		9%	5%	6%	17%	23%	27%	13%

*** = significant at $\alpha = 0.01$, ** = significant at $\alpha = 0.05$, * = significant at $\alpha = 0.10$. (Shading indicates significant entries).

Respondent attitudes towards climate change and future energy needs ranked origin (produced in Tennessee) as an undesirable feature among the set of product attributes. Those more concerned about climate and energy were 1.35% more likely to rank *origin* as a desirable product characteristic. Respondents reporting higher levels of educational attainment (*college*) were more likely to rank the renewable fuel co-product attribute of the biochar-amended potting soil (0.88%). However, gardening enthusiasts were less likely to rank this feature as the ‘best’ attribute of the product (−0.38%).

With respect to the biochar source, frequent buyers of potting soil ranked food waste-to-biochar as the most attractive feature of the hypothetical potting mix. Gardening enthusiasts were also more likely to rank the biochar source ‘agricultural by-product’ biochar-enhanced potting mix as the most desirable feature.

The probabilities an attribute ranked ‘best’ were calculated using the ASROP estimates and evaluated for each record in the survey (Table 6). Biochar sources dominated the rankings, with agricultural by-products (27%), food waste (23%), and wood waste (17%) as the most desirable product features.

5. Conclusions

Private-sector investment in renewable energy technology and production is modest with respect to mandated goals set by the Renewable Energy Act of 2005. Feedstock supply logistics, the scalability of advanced biofuel processes to industrial levels, and over a decade of relatively low fossil fuel prices have frustrated efforts to develop bio-based fuels. Coupled with limited or uncertain availability of reliable feedstock resources, entry costs dissuade private sector investment in capital resources required for starting up advanced biofuel facilities, which results in near-zero or negative profit margins. Facilities currently in the business of producing renewable energy sources from biomass have adapted to this adverse climate by adding value to co-products generated by the fuel production process.

Pyrolysis, torrefaction, and other thermolytic process used to manufacture advanced biofuels produce a number of co-products with potential market value. Biochar is one such co-product that could be used as a soil amendment for agricultural production, or mixed with home-and-garden soil products. Consumer demand for home and garden products has been robust and continues to grow following the economic re-bounce from the Great Recession.

This study was part of a larger project investigating the feasibility of advanced biofuel production in Tennessee, and more generally in the southeastern US. The study used a survey of Tennessee home gardeners to determine which product attributes would be most desirable in terms of purchasing a potting soil product amended with biochar. Consumer preferences for a hypothetical potting mix enhanced with biochar were estimated using a best-worst procedure. If such a hypothetical market were to develop for home garden soil amended with biochar, then retail outlets might consider branding the product's biochar source as a renewable fuel co-product or as originating from incinerated food waste. Retailers might also consider avoid using labels indicating the material was certified as a bio-based product through programs supported by federal agencies.

Our findings are not without limitations. Respondents may not have a clear understanding of the attributes defining a product, thereby conflating distinct attributes and biasing estimates of preference rankings. Our empirical analysis suggested a method whereby the design of the best-worst survey structure was used to restrict correlations between attributes using an alternative-specific rank ordered probit regression, thereby modeling directly correlations between attributes. The generalizability of these findings is somewhat limited because the survey only focuses on households in Tennessee. While the in-sample demographic statistics suggest our respondents were similar to a household gardener profile reported in a national survey, wider geographic coverage would be required to make further generalizations.

Consumer preferences for numerous other bioenergy production co-products could be studied using choice experiment survey methods. Cosmetics, food additives, construction materials, household cleaning products, soaps, disposable utensils and eating-ware, and packaging are a few examples of common consumer products that could be made with biofuel co-products. In-sample results from this study suggest that consumers place more importance on the feedstock source used to produce biochar, specifically agricultural by-products and food waste. Older, more conservative individuals were less inclined to rank USDA certification of the bio-based product as being the 'best'. From the marketing standpoint of retailers providing home and garden services, labeling soil mixture amended with biochar as 'sources from farms' or 'recycled food waste' might attract a specific segment of home gardeners to purchase such a product. Such efforts could indirectly 'backward-link' home gardeners to the farm sector, thereby providing farm operators an opportunity to produce dedicated energy crops. Biofuel facilities could also capture some share of this market, thereby potentially increasing profit margins in the biobased product markets. Finally, biochar could serve as a final pathway in a closed-loop cycle of biomass production, conversion of biomass to energy, and soil health sustainability.

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Appendix A.

Table A1. Frequency of Best and Worst on Alternatives for Attributes.

Attribute	Level	Worst	Tied	Best	Total
100% certified USDA	No	1752	1501	267	3520
	Yes	265	1601	1654	3520
Produced in Tennessee	No	1463	1875	182	3520
	Yes	487	1889	1144	3520
Renewable biofuel co-product	No	1381	1867	272	3520
	Yes	534	1902	1084	3520
Source	Ag. by-product	296	732	732	1760
	Food waste	258	887	615	1760
	Non-food energy crop	374	844	542	1760
	Wood waste	230	982	548	1760
Total		7040	14080	7040	28160

Appendix B. Covariance Matrix for the Alternative-Specific Rank Ordered Probit Regression

The estimated covariance matrix is

$$\mathbf{M}\mathbf{M}' = \begin{bmatrix} 2 & & & & & & \\ 1.13 & 2.03 & & & & & \\ 1.16 & 1.14 & 2.08 & & & & \\ 1.06 & 1.13 & 1 & 2.26 & & & \\ 1.10 & 1.11 & 1 & 1 & 2.31 & & \\ 1.14 & 1.10 & 1 & 1 & 1 & 2.09 & \end{bmatrix}$$

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