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**The Western Economics Forum**
A peer-reviewed publication from the Western Agricultural Economics Association

**Purpose**
One of the consequences of regional associations nationalizing their journals is that professional agricultural economists in each region have lost one of their best forums for exchanging ideas unique to their area of the country. The purpose of this publication is to provide a forum for western issues.

**Audience**
The target audience is professional agricultural economists with a Masters degree, Ph.D. or equivalent understanding of the field that are working on agricultural and resource economic, business or policy issues in the West.

**Subject**
This publication is specifically targeted at informing professionals in the West about issues, methods, data, or other content addressing the following objectives:

- Summarize knowledge about issues of interest to western professionals
- To convey ideas and analysis techniques to non-academic, professional economists working on agricultural or resource issues
- To demonstrate methods and applications that can be adapted across fields in economics
- To facilitate open debate on western issues

**Structure and Distribution**
The *Western Economics Forum* is a peer reviewed publication. It usually contains three to five articles per issue, with approximately 2,500 words each (maximum 3,000), and as much diversity as possible across the following areas:

- Farm/ranch management and production
- Marketing and agribusiness
- Natural resources and the environment
- Institutions and policy
- Regional and community development

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Comparing Locally Oriented and Mainstream Farming: Observations from the Oregon Blueberry Industry

Wesley Bignell

Introduction

Local food continues to grow in popularity among consumers and gain interest among policy makers. Many large grocery chains, hospitals, and schools have begun to source products from local farms. The U.S. Department of Agriculture has launched initiatives such as “Know Your Farmer, Know Your Food” to expand local food markets. While local food sales represent a small share of total agricultural sales, growth in this sector could reshape where food is grown, how far it travels, and the composition of farms that supply the nation’s food. This paper helps improve understanding of the local food trend by examining how the characteristics, motivations, and information networks of locally oriented farms differ from farms that focus on mainstream markets.

Previous studies indicate that locally oriented farms differ in a variety of ways. On average, farms that sell locally and/or direct-to-consumer are smaller (Martinez et al., 2010; Starr et al., 2003; Monson, Mainville, and Kuminoff, 2008). They are also more likely to sell fruits and vegetables (Ostrom and Jussuaume, 2007; Detre, Mark, Mishra, and Adhikari, 2009), grow a diverse variety of crops (Starr et al., 2003), and use organic production methods (Detre et al., 2011; Martinez et al., 2010; Ostrom and Jussuaume, 2007; Monson, Mainville, and Kuminoff, 2008). Operators of locally oriented farms tend to be younger (Uematsu and Mishra, 2011), more educated, and less experienced (Low and Vogel, 2008; Monson, Mainville, and Kuminoff, 2008).

This paper compares three types of farms – those that sell almost exclusively through mainstream, non-local supply channels (mainstream); those that sell almost exclusively through local channels (local); and those that sell through a combination of local and mainstream channels (combination). The results show that, among the farms in the study, those farms selling primarily through mainstream channels systematically differ from farms that sell locally. Overall, the local farms are smaller, more recently established, less capital intensive, and less profit-oriented. Combination and local farms also differ. The local farms are smaller and newer than combination farms. Compared with mainstream or combination producers, local producers are less experienced and more interested in using their farms to accommodate their lifestyles and personal values. Analysis of the data reveals that differences between each of these types of farms are driven by the economic and social contexts of mainstream and local markets as well as by the personal characteristics of the producers who self-select into each market.
Study Location, Definitions, and Method

The study looked in detail at one agricultural product (blueberries) in one growing region (Oregon’s Willamette Valley). The Willamette Valley region is a major center of blueberry production with over 800 farms and over 6000 acres planted (USDA, 2009). The region is also home to a thriving local food movement with over 60 farmers markets and several organizations that facilitate and promote local food markets. In the Northwest U.S., 18 percent of farms sold through direct supply chains compared with six percent nationally in 2007 (King et al., 2010). Fresh direct-to-consumer blueberries are widely available in this region through u-picks, farm stands, and farmers markets. However, the quantity of blueberries produced in the area far exceeds local demand.

Across the local food movement and local food research, definitions of 'local' vary considerably (Hand and Martinez, 2010). This study defines 'local' as the Willamette Valley region and 'local food' as any food that farm operators produce and sell directly to local consumers or through channels specifically targeting local consumers. Farms are divided into the mainstream, combination, and local categories based on an estimate of the proportion of each farm’s sales that are local.3,4

The study’s purpose is to develop insights into the marketing strategies pursued by different types of farms. In order to explore several aspects of different marketing arrangements, an exploratory multiple case design was used (Yin, 1994).5 Both farms and marketing categories are used as cases at two distinct levels of analysis. Farm cases were selected based on geographic location and publicly available information about their marketing practices. Only farms with at least one full-time, primary farming occupation owner were considered. Data were collected in spring of 2009 through on-farm interviews, observation of relevant farm-related events, and compilation and review of publicly available documents on the farms and markets studied. The general research strategy was to (1) purposefully select a small number of farms using the above criteria, (2) collect and organize data about those individual farms, (3) analyze the data at the individual farm level, (4) compare individual farms for similarities and use that as the basis for determining category level characteristics among farms with shared marketing practices, and (5) compare differences among marketing categories.

Results

Farm Characteristics

The results reveal clear differences between local, combination, and mainstream farms. Table 1 (below) shows how farms in each category compare in size, production, employment, and years of operation. The three mainstream farms are characterized by large size, specialized labor forces, and capital-intensive operations. They range in size from 250 to 1000 acres and produce between 655,000 and 2.1 million pounds of blueberries annually. Each farm produces only a few crops and emphasizes blueberries. Two of the farms were established over 70 years ago.

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3 In practice, dividing the farms into three categories was not difficult because the mainstream farms sold almost nothing locally, the combination farms all relied significantly on both local and mainstream sales, and none of the local farms indicated any sales outside of local channels or outlets.

4 Classification is based solely on owners’ responses to questions regarding how they sell their products and independent of any other information about the farm.

5 Exploratory qualitative research methods have been advocated by many economic researchers (Bitsch, 2005; Piore, 2006; Westgren and Zering, 1998; Blinder, 1990; Bewley 2002).
The other is less than 20 years old, but the owner has worked in the blueberry industry much longer.

Each mainstream farm maintains a year-round specialized staff that includes multiple tiers of management and employs between 175 to 400 workers during harvest. Two of these farms have large technologically advanced packing, processing, and storage facilities. The other mainstream farm focuses on production and continuously seeks out and experiments with new technologies and practices.

<table>
<thead>
<tr>
<th>Table 1. Farm Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mainstream</strong></td>
</tr>
<tr>
<td>Production Acreage</td>
</tr>
<tr>
<td>Blueberry Acreage</td>
</tr>
<tr>
<td>Blueberry Production (lbs)</td>
</tr>
<tr>
<td>Employees (peak)</td>
</tr>
</tbody>
</table>

In contrast, the five local farms are small and run by a single individual or household. Three local farms focus almost exclusively on blueberries, one focuses on strawberries, and one is more diversified. They range in size from 1 to 12 acres and produce between 200 to 55,000 pounds of blueberries annually. They were established relatively recently, with the oldest founded in the early 1990’s.

The local farms perform production and retailing for most of what they sell and operations are much less capital intensive. Owners complete most tasks themselves and hire additional labor on a seasonal or as needed basis. Two of the farms employ one year-round part-time employee. Because they are much smaller, the local farms employ only five to fifteen people during harvest season.

The five combination farms fall very much between the mainstream and local farms in each of the factors considered. They are larger than any of the local farms and smaller than any of the mainstream farms. Four of the farms have between one and eight year-round employees. Two of the farms focus primarily on blueberries, one focuses on strawberries, and two produce a diverse variety of crops. Local direct-to-consumer sales are the first priority for four of the five combination farms. The fifth farm uses direct-to-consumer sales as a means of advertising to generate interest among local and non-local retail outlets and consumers to purchase through mail order.

One combination farm has a technologically advanced packing and processing facility. This producer has ambitions to expand his operation and serve a larger, more geographically dispersed set of buyers. The other combination farms do not have the same post-harvest equipment, though they do own or lease large-scale production equipment.

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6 Farm size was generally unknown prior to the interviews, but it turned out to be perfectly aligned with marketing practices with mainstream farms being the largest and local farms the smallest. Ideally, there would have been some overlap in size among the marketing categories.
Consistent with previous studies, the cases in this study suggest that the decision to sell through local marketing channels is related systematically to farm size. The variation in labor specialization and capital intensity likely follows from differences in size and may also be attributed in part to the local producers’ interest in low-tech, ‘sustainable’ practices and contentment with their current levels of production.

**Producer Background and Motivations**

Many factors enter into a producer’s farm decisions. These decisions depend in part on the knowledge the producer derives through experience and training. Table 2 (below) shows each producer’s family background in agriculture and indicates college education in an agricultural field. Farm decisions may also depend on the producer’s preferences for certain types of work (Key and Roberts, 2009; Hunt, 2007) or providing social or environmental goods (Alkon, 2008; Chouinard, Paterson, Wandschneider, and Ohler, 2008; Lichtenberg and Zimmerman, 1999; Starr et al, 2003). Table 3 (below) summarizes the interview responses of farm owners regarding the choice to own and operate a farm.

### Table 2. Producer Background in Agriculture

<table>
<thead>
<tr>
<th></th>
<th>Mainstream</th>
<th>Combination</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grew up on Family Farm</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Worked on Family Farm</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>College Ag Education</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

All of the mainstream producers grew up farming and all have family ties to the blueberry industry. Two mainstream producers took over well-established blueberry farms and packing and processing operations from their parents. The other mainstream producer grew up on a farm and learned the blueberry business through working for a well-established blueberry operation owned by a family member. In the interviews, the mainstream producers explained that some of their decisions were based on their preferences for engaging in certain tasks, but throughout their responses they made clear that their central concern is to maximize profit.

Two local producers grew up on a family farm, but neither indicated having had an active role in its operation. One learned to grow blueberries through conversations with other nearby growers in the year before establishing his farm. The other learned through trial and error and by spending time with a family member who farms. Of the local producers who did not grow up farming, two learned agriculture through gardening and one learned by doing after purchasing the farm.

Lifestyle and values are particularly important for local producers. They all acknowledge that they want their farms to provide income, but none expressed interest in significantly expanding her operation. They indicated that they farm for the lifestyle and enjoy living on the farm and having the opportunity to interact with customers. They also indicated the importance of using their farms to demonstrate sustainable farming practices and serve their communities.

Four combination producers grew up farming. Two took over well-established blueberry farms from their parents. Two others earned bachelor’s degrees in agricultural fields, worked in jobs related to agriculture, and saved until they were able to purchase their own farms. One combination producer, however, was raised in a suburban community and acquired his knowledge of agriculture through work experience on an organic farm.
Like the mainstream producers, the combination producers expressed a focus on operating a profitable business. All of the combination producers, however, placed considerably more emphasis on locating outlets with greater price stability and where they had more influence in negotiations than with their current mainstream buyers. Four of the combination producers indicated enjoying the farming lifestyle and working hard to remain in the industry. Two combination producers indicated a strong value orientation in their production practices. One focuses on food nutrient content. The other is developing farming techniques that go beyond organic standards and uses the farm to educate customers about his practices and provide food to local charities.

Table 3. Producer Motivations to Own and Operate a Farm

<table>
<thead>
<tr>
<th></th>
<th>Mainstream</th>
<th>Combination</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income/Profit</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Run Own Business</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Enjoys Production</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Enjoys Marketing</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Interact with Other Farmers</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Farming Lifestyle</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Continue Family Business</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Good for Family/Children</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Interact with Customers</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Customer Satisfaction</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Customer Health</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Community Involvement</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Protect Environment</td>
<td>•</td>
<td>•</td>
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</tr>
</tbody>
</table>

The producers’ background and motivations reveal important differences between farms. The local producers have less extensive backgrounds in agriculture than the mainstream or combination producers. Rather than learning through experience on their family’s farm or through formal agricultural education, they learned through gardening experience, neighboring farms, and trial and error. They are also less concerned with maximizing profit than mainstream or combination farms.

**Producer Information Linkages**

In addition to knowledge and personal motivations, producer decisions also depend on access to information. The figure below shows linkages between case farms and the groups that provide them with important information for their production and marketing decisions. It reveals that the mainstream, combination, and local producers in this study occupy different positions within blueberry-related information sharing networks.

The mainstream producers share with other participants in the blueberry industry locally, nationally, and internationally, and with organizations and researchers who support that industry. Local producers share information primarily with other locals, including local producers, community organizations, consumers, and gardeners. While both local and mainstream
producers participate in commodity associations and interact with university researchers, those interactions are qualitatively different because each of the mainstream producers holds a leadership position in at least one association, which they claim provides them with better access to important participants in the blueberry industry and better access to researchers. Local producers have very limited connections to participants in the mainstream blueberry industry, particularly to large-scale buyers and international producers. Mainstream and local producers also report relatively limited interaction with one another.

Figure. Important Information Sharing Linkages for Case Farms

Though the mainstream and local producers are largely segregated in terms of utilized information sources, both groups interact with combination producers. The combination producers' information seeking behavior overlaps that of both local and mainstream producers. They report receiving important information from large buyers, local retailers, and consumers, and actively participate in both commodity associations and community organizations. Two of the combination producers are involved in ongoing university research projects. This overlap in information sharing with participants in both mainstream and local markets provides a communication bridge between the two groups.
Discussion

Consistent with previous literature on local marketing, this study finds that farm size and local sales are directly related. Interviews suggest local markets are too small to absorb very large quantities of a single product and require too many small transactions to be attractive to large farms. Even as some combination farms expand their local sales, they expressed that they would continue to have excess production for the foreseeable future. At the same time, however, even the larger combination farms have difficulty competing in mainstream markets. Four combination farms in this study started out selling only to mainstream buyers, but turned to local sales because the prices in the mainstream markets were too low and unstable to be profitable at their relatively moderate scales of production. The small local farms are not interested in entering mainstream markets for a variety of reasons including lack of profitability, risk, desire to interact with customers, and even moral opposition to mainstream agricultural markets.

This study also found that information sharing and utilization capacities provide larger farms with an important advantage in mainstream markets. Production practices and crop varieties continuously evolve and producers must keep up with new developments in order to remain competitive. Additionally, identifying and communicating with buyers is an information and time intensive process. Mainstream farms have large internal organizations. The owners and their staff can dedicate more time to attending events, monitoring market conditions, conducting transactions, staying current on new production practices, and conducting on-farm experiments. The time and expense that large farms dedicate to these peripheral activities costs less per unit than for smaller farms.

Similarly, the producers in this study who grew up and worked on their families’ mainstream farms, which include four of the five combination producers, have a more competitive position in mainstream agriculture. They are familiar with running large-scale operations and selling to large mainstream buyers. Their existing relationships with industry actors and other mainstream farmers help to connect them to resources and opportunities, verify reputations when needed, and quickly solve problems. Additional experience reduces the expense of learning and important social ties reduce search and information costs relative to less experienced and less connected farmers.

Local farms lack the land, equipment, mainstream connections, and experience of mainstream and combination farms. The owners, however, have a broader set of motivations for farming and their decisions depend less directly on the desire to maximize profits. Some local farm owners claim to make very modest incomes, much lower than if they worked in a different occupation. They also show very little interest in increasing the scale of their operations. These producers turned to agriculture for the lifestyle and the opportunity to express their values. Local food markets allow them to live on a farm, work outside, use their preferred production practices, interact with community members, and provide public services.

Conclusion

This set of case studies helps provide a better understanding of how and why farms that pursue local market channels differ from those that focus on mainstream channels. Large, well-established, well-connected blueberry farms have important economic advantages that are unavailable to other farms. Their scale of production and low per unit costs allow them to compete more effectively in mainstream markets, which makes those markets more economically attractive to them relative to other farms. Local food markets enable smaller farms with owners who value nonpecuniary aspects of the farming occupation to stay in business and
continue to develop innovative practices, provide specialized products, and personally engage
with local businesses and consumers.

At present, there are relatively few economic studies regarding why farms sell through local
marketing channels. Future research should consider the range of benefits that accrue to locally
oriented farm owners through their work, and attempt to value those benefits and assess their
impact on farm decisions. Future research should also investigate how local food markets are
changing over time. In particular, some major grocery chains are attracting larger farms and
suppliers to local sales by offering an opportunity to fill large orders at prices above wholesale.
These new entrants could impact prices received by existing local farms and, in turn, the
composition of farms that sell local food.

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It’s All About Produce: Flexing the Muscles of Western U.S. Organic Spinach Consumption

Christiane Schroeter and Xiaowei Cai

Introduction

Over the past few decades, consumers have become more concerned about health and nutrition, which is displayed by an increased demand for organic foods. Once considered a niche product, organic food has become more affordable for consumers through its availability in conventional supermarkets. In 2010, organic food and beverages showed a 7.7% increase in annual sales compared to 2009 sales, with the highest growth rate of 11.8% in organic produce (Organic Trade Association (OTA), 2011).

Organic produce has been considered a “gateway product.” These products form the first organic purchasing experience, which is then widened to include other organic products (Hartman Group, 2000 and 2002). Responding to the growing popularity of organic produce, its production has more than doubled since the late 1990s. Currently, all U.S. states grow certified organic crops (The Food Institute, 2009). The competition in the organic food market is increasing due to more firms participating in the industry (Dimitri and Oberholtzer, 2009). Thus, producers have expressed an interest in determining and refining their target market.

Given that multiple venues such as specialized food stores and farms with direct sales offer organic produce, its customer base appears to have become more diverse (Dimitri and Greene, 2002; Stevens-Garmon, Huang, and Lin, 2007). There are a variety of demographic factors, such as age, gender, and income level that are important for the individual food choice. Food environmental variables, such as the number of specialty supermarkets in a shopper’s neighborhood and fast food expenditures might also impact an individual’s purchasing decision of organic foods. These food environmental factors have an increasingly important effect on a household’s produce choice, along with the demographic determinants (Sturm and Datar, 2005).

Current economic studies that focus on organic food consumption present limited information about the profile of the organic spinach consumer. The range of factors has been restrictive, limited to either demographic or socio-economic determinants. To our knowledge, no comprehensive assessment of organic produce purchasing decisions with food environmental information has been performed. There is need for research that evaluates actual purchasing decisions of organic foods, together with information about demographic, socio-economic, and food environmental variables (e.g. Onyango, Hallman, and Bellows, 2006; Dettmann and Dimitri, 2007).

The objective of this study is to analyze the purchasing factors of organic spinach in the Western United States. Specifically, this study determines the impact of demographics, socio-economics, and the food environment on (1) the purchasing likelihood of organic spinach and (2) expenditure shares of organic spinach. California and Arizona produce 85% of the U.S. supply of spinach, and households in the Western U.S. purchase more organic produce than those residing in other regions (U.S. Department of Agriculture-Economic Research Service

1 The authors are assistant professors in the Agribusiness Department at California Polytechnic State University, San Luis Obispo. They would like to thank the Agribusiness Department for the purchase of the IRI data set. In addition, the comments of Don McLeod and two anonymous reviewers were greatly appreciated.
Thus, this study focuses on organic spinach purchases in the Western states, which will provide a significant research contribution.

Developing a better understanding of factors that impact organic spinach purchases can lead to more efficient decisions by producers, food businesses, consumers, and policy makers. The availability of this information could help manufacturers develop products which better correspond to consumer tastes and preferences. Organic food distributors will benefit by developing more effective marketing strategies in a more competitive and saturated market for organic produce, and an opportunity to expand market share. Finally, consumers will benefit by a greater availability of products and information that meet their needs and circumstances.

**Empirical Background on Organic Spinach Demand**

Organic spinach has increased in popularity due to the availability of the convenient triple-washed cello-packed version, also called ‘bagged organic spinach’. With regard to the produce purchasing decision, convenience is an important decision factor. Over the past two decades, the value of time has been altered by several demographic and societal changes. The individual cost of nutritional and leisure time choices has increased, and thus, convenience plays an important role in consumers’ food choices.

Given the convenience of bagged spinach, the conventional and organic versions have become one of the fastest growing segments of the packaged salad industry (USDA-ERS, 2007). Figure 1 shows the sales trend of total and organic bagged spinach in the Western U.S. over time. Organic spinach sales increased by 250% from 2007 to 2010, while total organic and conventional spinach sales increased by 57% during the same time (Information Resources, Inc. (IRI), 2011).

**Figure 1: Bagged Total and Organic Spinach Sales in the Western U.S., 2007-2010 (Information Resources, Inc. (IRI), 2011)**

One driving force for the increased demand for convenience food might be a higher number of women working, particularly mothers, which may lead to an increase in households with both parents in the work force. Placing a higher value on labor market time leads to decrease in the time spent in the household, and thus, less time can be devoted to preparing meals for the family (Capps, Tedford, and Havlicek, 1985; Chou, Grossman, and Saffer, 2004).
in home time has increased the demand for easy-to-prepare meal solutions, such as bagged spinach.

Previous studies determined the impact of household demographic variables such as ethnicity, age, income, gender, and education influence consumer’s organic food purchase behavior (e.g. Dettmann and Dimitri, 2007; Li, Zepeda and Gould, 2007; Zhuang, Dimitri and Jaenicke, 2009). According to popular perception, organic consumers are white, wealthy, and have young children (Stevens-Garmon, Huang, and Lin, 2007). However, other findings suggest that frequent buyers of organic produce are African-Americans, Asian, or Hispanics and earn lower to mid-range incomes. Lower-income families might choose to buy organic when possible, as a means of preventative medicine (Hartman Group, 2003). Thus, given these mixed results, it is important to investigate the role of demographics and socio-economics such as food security in organic food choices.

Furthermore, households with working parents might go out more often for meals or buy take-out (Capps, Tedford, and Havlicek, 1985; Chou, Grossman, and Saffer, 2004). A loss of proper cooking skills increases the need to eat convenience food or food away from home (European Food Information Council, 2005). Another factor contributing to the increased demand for food away from home is the fact that the per-capita number of fast food restaurants doubled between 1972 and 1997, which reduces the search and travel time (Chou, Grossman and Saffer, 2002). Aertsens et al. (2009) gave a comprehensive review on the determinants of organic food consumption and concluded consumers’ organic food choice is affected by numerous macroeconomic and general food environment factors. Thus, there is a need to include food environmental variables such as food accessibility into the specification for the profile of the organic spinach consumer.

Data

We use the 2007 Symphony IRI Group of Information Resources Inc. (IRI) National Consumer Network Panel on individual households’ pre-packaged spinach purchases in the U.S. Western region (IRI, 2011). The panel is based on demographically representative sample of 100,000 households nationwide. Panel members could either be volunteers or recruited by IRI. After their purchase, participating households used hand-held scanners to record the dates of spinach purchases, Universal Product Code (UPC) code, purchase volume, and total expenditures. Random weight purchases, such as of fresh loose-leaf spinach, are not included in the data set (Lusk and Brooks, 2011).

The IRI Consumer Panel also provides associated household demographic information (IRI, 2011). In addition, we added socio-economic and food environmental factors that might influence the individual household’s choice for organic spinach, and the expenditure share on organic spinach.

The socio-economic and food environmental variables are collected from the 2007 Food Environment Atlas based on each household’s Federal Information Processing Standards (FIPS) code (USDA-ERS, 2010). FIPS codes uniquely identify geographic areas (U.S. Census Bureau, 2011). The data from the Food Environment Atlas includes FIPS code-specific information about household-level food insecurity, information about food accessibility, fast food expenditure per capita, three different related price ratios, and the local organic food availability.

2 Given the time of the data collection, our analysis does not account for the 2006 E.coli outbreak in spinach.
Our final sample includes 2,607 households residing in the U.S. West that purchased spinach at least once during year of 2007. This spinach purchase could be either organic or conventional, or a mix of these two types. This study employs four groups of variables: 1) spinach purchase information; 2) demographics; 3) socio-economics, and 4) food environment information.

Table 1 shows the definitions, means and standard deviations of each variable used in the estimations. The table is divided into five categories of variables. While the likelihood of purchasing organic spinach and the organic spinach expenditure share served as our dependent variables, the remaining four variable categories were used as independent variables in our analyses.

As indicated in Table 1, 29% of the households had purchased organic packaged spinach during 2007, with a 21% expenditure share of organic vs. total spinach. As calculated from the IRI data set, the average price of organic spinach in the Western U.S. is $5.33 per pound. The average household expenditures and purchases of organic spinach are $2.38 and 0.4 pounds, respectively.

About 41% of the participating households are California residents. Per household member, the average income is $28,514 and 82% are white. Of all household heads, 48% earned a college or post-graduate degree. Of all male household heads that purchased spinach at least once during 2007, only 2.1% could be classified as young, while 29.5% belong to the mid-aged category. A mid-aged female resides in 47% of the households and only 9% of the households have children younger than 6 years of age. The majority, 66%, of the household heads is married.

Regarding socio-economics, we utilized the food insecurity prevalence from the USDA-ERS Food Atlas. The prevalence includes households with low and very low food security by state relative to the national average, according to an annual survey conducted by the U.S. Census Bureau. The food security status of the household was assessed based on the number of food-insecure conditions reported, such as being unable to afford balanced meals, cutting the size of meals or being hungry because of too little money for food (USDA-ERS, 2010).
<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dependent variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic</td>
<td>1 = if Household has purchased organic spinach in 2007</td>
<td>0.289</td>
<td>0.453</td>
</tr>
<tr>
<td>Organic share</td>
<td>Organic spinach expenditure/total spinach expenditure</td>
<td>21.177</td>
<td>36.860</td>
</tr>
<tr>
<td><strong>Spinach purchase information</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinach price</td>
<td>Price of organic and conventional spinach calculated by household reported expenditures/purchase quantities, $/lbs</td>
<td>5.325</td>
<td>2.766</td>
</tr>
<tr>
<td>Organic expenditure</td>
<td>Average household total expenditures in $ for organic spinach</td>
<td>2.380</td>
<td>7.192</td>
</tr>
<tr>
<td>Organic purchase</td>
<td>Average household total organic spinach purchase volume, lbs</td>
<td>0.402</td>
<td>1.352</td>
</tr>
<tr>
<td>Spinach purchase</td>
<td>Average 2007 household total spinach purchase volume, lbs</td>
<td>1.830</td>
<td>2.493</td>
</tr>
<tr>
<td><strong>Demographics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>California</td>
<td>1 = if household is located in California</td>
<td>0.414</td>
<td>0.493</td>
</tr>
<tr>
<td>HH Income</td>
<td>Mean of each annual household income category per household member in $1,000s $4.999 if x&lt;$10; $17.499 if x&lt;$20; $22.499 if x&lt;$25; $42.499 if x&lt;$50; $62.499 if x&lt;$75; $87.499 if x ≥$75</td>
<td>28.514</td>
<td>15.601</td>
</tr>
<tr>
<td>White</td>
<td>1 = if Household head is white</td>
<td>0.821</td>
<td>0.383</td>
</tr>
<tr>
<td>College</td>
<td>1 = if Household head has graduated from college</td>
<td>0.343</td>
<td>0.475</td>
</tr>
<tr>
<td>Post graduate</td>
<td>1 = if Household head has a post-graduate degree</td>
<td>0.145</td>
<td>0.353</td>
</tr>
<tr>
<td>Male young</td>
<td>1 = male and 18 ≤ age ≤ 34</td>
<td>0.021</td>
<td>0.144</td>
</tr>
<tr>
<td>Male mid-aged</td>
<td>1 = male and 35 ≤ age ≤ 54</td>
<td>0.295</td>
<td>0.456</td>
</tr>
<tr>
<td>Female young</td>
<td>1 = female and 18 ≤ age ≤ 34</td>
<td>0.035</td>
<td>0.184</td>
</tr>
<tr>
<td>Female mid-aged</td>
<td>1 = female and 35 ≤ age ≤ 54</td>
<td>0.470</td>
<td>0.499</td>
</tr>
<tr>
<td>Young children</td>
<td>1 = HH has only children younger than 6 years of age</td>
<td>0.092</td>
<td>0.290</td>
</tr>
<tr>
<td>Married</td>
<td>1 = if Household head is married</td>
<td>0.658</td>
<td>0.474</td>
</tr>
<tr>
<td><strong>Socio-economics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH no car</td>
<td>% of housing units in a county that are more than ten miles from a supermarket or large grocery store and have no car</td>
<td>0.111</td>
<td>0.524</td>
</tr>
<tr>
<td>Food insecurity</td>
<td>Prevalence of household-level food insecurity by State relative to the national average, takes values as -1, 0, or 1, with 1 being extremely insecure and -1 being the least insecure</td>
<td>0.536</td>
<td>0.709</td>
</tr>
</tbody>
</table>
Table 1 cont.: Descriptive Statistics (N = 2,607)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast food</td>
<td>Average annual expenditures (in 2007 dollars) per capita on food purchased at limited-service restaurants for county residents</td>
<td>740.242</td>
<td>59.214</td>
</tr>
<tr>
<td>Green leafy/starchy</td>
<td>Ratio of the regional average price ($/gram) of dark green vegetables to the regional average price ($/gram) of starchy vegetables</td>
<td>1.374</td>
<td>0.099</td>
</tr>
<tr>
<td>Fruit/sweet</td>
<td>Ratio of the regional average price of fruit to the regional average price of packaged sweet snacks</td>
<td>0.303</td>
<td>0.034</td>
</tr>
<tr>
<td>Fruit/savory</td>
<td>Ratio of the regional average price of fruit to the regional average price of packaged savory snacks</td>
<td>0.361</td>
<td>0.029</td>
</tr>
<tr>
<td>Farms</td>
<td>Number of farms in the county that sell directly to final consumers</td>
<td>182.564</td>
<td>170.875</td>
</tr>
<tr>
<td>Specialized stores</td>
<td>Number of specialized food stores in the county per 1,000 people</td>
<td>0.099</td>
<td>0.038</td>
</tr>
</tbody>
</table>

On average, the price of dark green vegetables is 37% higher than the regional price of starchy vegetables. The starchy vegetables include plain and frozen potatoes, corn, lima beans, and green peas. The average price of dark green vegetables is about 30.3% and 36.1% of the average packaged sweet snacks and packaged savory snacks. Sweet snacks include cookies and candy bars, while savory snacks include potato chips, pretzels and crackers. All the regional average prices are in $ per gram.

Variables such as the number of farms with direct sales and the number of specialized food stores are used to measure organic food accessibility. The farm count is included in our analysis to pick up the urban and rural split. According to the USDA-ERS Food Atlas (2010), specialized food stores include outlets mainly engaged in retailing specialized foods such as retail bakeries, meat and seafood markets, dairy stores, and produce markets.

Figure 2 shows the household expenditure share of organic fresh spinach in the eleven Western states that are represented in our data set. With 33.97%, Colorado has the highest organic spinach expenditures per the total spinach expenditures, while New Mexico shows the lowest organic spinach expenditure share with 9.84%.
Methodology

Following Dettmann and Dimitri (2007), we are using the Heckman two-step selection model. This model generates consistent and asymptotically efficient parameter estimates compared to the standard regression methods (Heckman, 1990). The application of the Heckman estimation procedure provided deeper insights regarding the main factors that drive consumers’ organic spinach purchase decisions.

There are two stages in Heckman’s estimation. In the first stage, equation (1) is estimated using logistic regression in order to understand how the individual household’s demographic, the socio-economic, and the food environmental variables impact the organic versus conventional spinach purchase decision. In the second stage, the organic spinach expenditure share is regressed on a group of household demographic, socio-economic and food environmental variables using a least squares estimation by taking into account the inverse Mills Ratio $\lambda$. The Mills Ratio is estimated from the first stage. It controls for the selection bias in order to provide consistent and efficient parameter estimates in the second stage.

With regard to our variable selection, there is a need for defining a profile of the organic food consumer, given the mixed findings of previous studies (e.g. Oberholtzer, Dimitri, and Green, 2008; Zhang et al., 2008). For instance, while some findings suggest that low-income households eat less produce than higher income households, other studies show that low-income households constitute more than half of the frequent organic food buyers (e.g. Hartman Group, 2002; Blisard, Steward, and Jolliffe, 2004; Dettmann and Dimitri, 2007; Zhang et al., 2008). Furthermore, consumer educational level will increase the chance of purchasing organic vegetables. Stevens-Garmon, Huang, and Lin (2007) also suggest that the heavy users of organic produce consist of college graduates.

Regarding the food environmental variables, we include the number of specialty food stores to measure access to organic produce. Although supermarkets are starting to carry more organic products, a specialized food store might be perceived as the more traditional retail outlet for organic products. This differentiation is based on the ongoing assertions that retailers, such as...
Wal-Mart, are labeling conventional food products as organic (Wong, 2007). Thus, we chose specialty stores to represent the organic food accessibility. The estimation of equation (1) is based on the individual household selection of organic spinach over conventional spinach:

\[
\text{Prob(Organic)} = \gamma_0 + \gamma_1 \text{Spinach price}_i + \gamma_2 \text{Organic purchase}_i + \gamma_3 \text{California}_i + \gamma_4 \text{HH Income}_i + \gamma_5 \text{White}_i + \gamma_6 \text{College}_i + \gamma_7 \text{Post graduate}_i + \gamma_8 \text{Male young}_i + \gamma_9 \text{Male mid-aged}_i + \gamma_{10} \text{Female young}_i + \gamma_{11} \text{Female mid-aged}_i + \gamma_{12} \text{Young children}_i + \gamma_{13} \text{Married}_i + \gamma_{14} \text{Food insecurity}_i + \gamma_{15} \text{Fast food}_i + \gamma_{16} \text{Farms}_i + \gamma_{17} \text{Specialized store}_i + \varepsilon_{1i}
\] (1)

In regression equation (1), the probability of household’s organic spinach purchasing behavior is a function of information regarding spinach purchases represented by the spinach price and the average total organic spinach purchase volume. The household demographic variables, such as whether the household resides in California, the household income, ethnicity, education, age, gender, and marital status are also included as independent variables. Socio-economic impacts are represented by the prevalence of household-level food insecurity. Furthermore, food environmental variables such as the annual fast food expenditures per capita, the number of farms with direct sales, and the number of specialized food stores are also included. The share of each household’s organic spinach expenditure is determined by various demographic, socio-economic, and food environmental variables and it is given by:

\[
\text{Organic share}_i = \beta_0 + \beta_1 \text{Organic expenditure}_i + \beta_2 \text{Organic purchase}_i + \beta_3 \text{Spinach purchase}_i + \beta_4 \text{California}_i + \beta_5 \text{HH Income}_i + \beta_6 \text{White}_i + \beta_7 \text{College}_i + \beta_8 \text{HH no car}_i + \beta_9 \text{Fast food}_i + \beta_{10} \text{Green leafy/Starchy}_i + \beta_{11} \text{Fruit/Sweet}_i + \beta_{12} \text{Fruit/Savory}_i + \beta_{13} \text{Farms}_i + \varepsilon_{2i}
\] (2)

The regression equation (2) includes some of the variables from the first stage. However, it expands the analysis by focusing on impacts that might directly influence organic spinach expenditures. Thus, we include three different local price indices of substitute or complement goods, such as prices of green leafy vs. starchy goods, and the ratios of the regional average price of fruit to the regional average prices of packaged sweet snacks, and savory snacks, respectively.

**Results**

We estimated a Heckman’s two-step regression using Stata version 10.1. The statistically significant Mills Ratio \(\lambda\) is the correlation coefficient between the two error terms in equations (1) and (2). We calculated the Wald statistics to test the joint significance of the model coefficients, i.e., the following hypothesis test was conducted: \(H_0: \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = \beta_7 = \beta_8 = \beta_9 = \beta_{10} = \beta_{11} = \beta_{12} = \beta_{13} = 0\). The null hypothesis is rejected at 1% significance level, which suggests the model variables are appropriate for jointly explaining the household organic spinach expenditure share.

Table 2 shows the marginal effect results from the logistic model in the first step. We find that with regard to spinach purchase information, a household that purchases one more pound of spinach is 3.9% point more likely to purchase organic spinach. Regarding demographics, a household with high income, high education levels, young children, and a young male or mid-aged female head, tends to purchase more organic spinach. Compared to the other races, a white household head has a 4.6% point lower chance of purchasing organic spinach.
Table 2: Logistic Estimation Results

<table>
<thead>
<tr>
<th></th>
<th>Marginal Effect</th>
<th>Std. Err.</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spinach purchase information</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinach price</td>
<td>0.087***</td>
<td>0.004</td>
<td>0.000</td>
</tr>
<tr>
<td>Spinach purchase</td>
<td>0.039***</td>
<td>0.004</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Demographics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>California</td>
<td>-0.041</td>
<td>0.025</td>
<td>0.107</td>
</tr>
<tr>
<td>HH Income</td>
<td>0.001*</td>
<td>0.0007</td>
<td>0.091</td>
</tr>
<tr>
<td>White</td>
<td>-0.046*</td>
<td>0.026</td>
<td>0.078</td>
</tr>
<tr>
<td>College</td>
<td>0.130**</td>
<td>0.055</td>
<td>0.019</td>
</tr>
<tr>
<td>Post graduate</td>
<td>0.138**</td>
<td>0.064</td>
<td>0.031</td>
</tr>
<tr>
<td>Male young</td>
<td>0.168*</td>
<td>0.091</td>
<td>0.066</td>
</tr>
<tr>
<td>Male mid-aged</td>
<td>0.004</td>
<td>0.022</td>
<td>0.847</td>
</tr>
<tr>
<td>Female young</td>
<td>-0.055</td>
<td>0.051</td>
<td>0.281</td>
</tr>
<tr>
<td>Female mid-aged</td>
<td>0.099*</td>
<td>0.052</td>
<td>0.056</td>
</tr>
<tr>
<td>Young children</td>
<td>0.062*</td>
<td>0.038</td>
<td>0.100</td>
</tr>
<tr>
<td>Married</td>
<td>0.032</td>
<td>0.021</td>
<td>0.137</td>
</tr>
<tr>
<td><strong>Socio-economics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food insecurity</td>
<td>-0.091***</td>
<td>0.015</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Food environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast food</td>
<td>-0.0005***</td>
<td>0.0002</td>
<td>0.002</td>
</tr>
<tr>
<td>Farms</td>
<td>0.0001**</td>
<td>0.00005</td>
<td>0.026</td>
</tr>
<tr>
<td>Specialized stores</td>
<td>0.863***</td>
<td>0.252</td>
<td>0.001</td>
</tr>
<tr>
<td>Mills Ratio λ</td>
<td>5.077**</td>
<td>2.014</td>
<td>0.012</td>
</tr>
</tbody>
</table>

***p<0.01, **p<0.05, *p<0.1

The socio-economic variable household food insecurity has a negative impact on the household’s organic spinach purchase. One point increase in the food insecurity index would decrease the household’s probability of purchasing organic spinach by 9.1% point. In addition, the food environmental factors significantly influence household organic spinach purchasing behavior. One more specialty store per 1,000 people would increase the household’s probability of purchasing organic spinach by 86.3% point. Interestingly, one more farm with direct sales only slightly increases the chance of organic spinach purchases, which might suggest that direct farm sales only contribute a small fraction to organic spinach purchases. Increasing the per-capita fast food expenditures would decrease the consumer’s selection of organic spinach by 0.05% point.

Table 3 shows our least squares estimation results from equation (2). Increasing organic spinach purchases by 1 pound would increase organic expenditure shares by 8.52% point. The total spinach purchase volume decreases the share of the organic spending by 8.91% point.
Table 3: Least Squares Estimation Results

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Err.</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constant</strong></td>
<td>185.915***</td>
<td>30.299</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Spinach purchase information</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic expenditure</td>
<td>0.726***</td>
<td>0.205</td>
<td>0.000</td>
</tr>
<tr>
<td>Organic purchase</td>
<td>8.524***</td>
<td>1.147</td>
<td>0.000</td>
</tr>
<tr>
<td>Spinach purchase</td>
<td>-8.911***</td>
<td>0.429</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Demographics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>California</td>
<td>-5.270*</td>
<td>3.102</td>
<td>0.089</td>
</tr>
<tr>
<td>HH Income</td>
<td>0.115**</td>
<td>0.055</td>
<td>0.037</td>
</tr>
<tr>
<td>White</td>
<td>3.142</td>
<td>2.199</td>
<td>0.153</td>
</tr>
<tr>
<td>College</td>
<td>2.970*</td>
<td>1.703</td>
<td>0.081</td>
</tr>
<tr>
<td><strong>Socio-economics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH no car</td>
<td>-0.174</td>
<td>1.464</td>
<td>0.905</td>
</tr>
<tr>
<td><strong>Food environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast food</td>
<td>-0.049***</td>
<td>0.0167</td>
<td>0.003</td>
</tr>
<tr>
<td>Green leafy/starchy</td>
<td>-37.692***</td>
<td>12.929</td>
<td>0.004</td>
</tr>
<tr>
<td>Fruit/sweet</td>
<td>68.162</td>
<td>46.007</td>
<td>0.138</td>
</tr>
<tr>
<td>Fruit/savory</td>
<td>-135.705**</td>
<td>61.738</td>
<td>0.028</td>
</tr>
<tr>
<td>Farms</td>
<td>-0.013**</td>
<td>0.006</td>
<td>0.041</td>
</tr>
</tbody>
</table>

***p<0.01, **p<0.05, *p<0.1

A California household, compared to a household from other Western states, tends to have a 5.27% point lower share of organic spinach expenditures. We find that a one-dollar increase in household income increases the organic spinach expenditure share by 0.12% point. A college graduate would spend 2.97% point more on organic spinach.

The food environmental factors have a significant influence on the organic spinach expenditure share. A one-dollar increase in the fast food expenditure per capita would decrease the household organic purchase share by 0.05% point. Increasing the price ratio between green leafy and starchy vegetables and the price ratio between fruit and savory snacks would significantly decrease the organic spinach expenditure share by 37.69% and 135.71% point, respectively. Therefore, as the price of dark green vegetables decreases by 1% relative to the price of starchy vegetables, the household’s spending on organic spinach would increase by 37.69% point. In addition, one more farm with direct sales would slightly decrease the household organic purchase share by 0.01% point.

Conclusions

The current study provides a unique contribution to literature, given the limited understanding of the new organic food consumer. Our paper expands the current literature, by examining the factors that both predict the selection of organic spinach and its purchase share. Through the empirical analysis of organic spinach purchasing behavior, we find that household food choices depend on several key demographic, socio-economic and food environmental determinants. Previous studies determined consumers in Western states have more access to organic produce than those residing in other regions (e.g. Stevens-Garmon, Huang, and Lin, 2007; Zhang et al. 2008). Interestingly, our estimation finds that California households spent a smaller expenditure share on organic spinach compared to non-California residents. This suggests that
households in California either spend less on organic spinach or purchase a large volume of total spinach compared to other Western states.

Our study provides insight into the role of household demographic characteristics on organic spinach purchasing behavior. We find that a household with high income, a high education level, and young children tends to choose organic spinach over conventional spinach. Thus, marketing strategies could target higher income and higher educated households. This could be beneficial with regard to increasing the expenditure shares of current consumers and attracting new customer (Zhang et al., 2008).

The results suggest that young male and mid-aged female household heads have a higher tendency towards purchasing organic spinach. This corresponds to the findings by Lin, Reed, and Lucier (2004), who determined that women 40 years and older eat the most spinach out of all female age groups. Additionally, white household heads, compared with other races, purchase less organic spinach, which is consistent with previous similar studies (e.g. Stevens-Garmon, Huang, and Lin, 2007; Zhang et al. 2008).

The food environmental impacts present interesting results with regard to organic spinach selection. Our study suggests that higher prices of green leafy and fruits relative to starchy vegetables and savory snacks could lead to an expenditure shift from organic spinach to the other goods. We find a large substitution effect between conventional and organic produce given consumers’ budget constraints.

Our study shows that increased organic spinach availability through specialized food stores is the largest contributor towards organic spinach purchase decision. This finding has been confirmed by the trend that specialty food stores are revolving around consumers seeking more variety such as environmentally friendly produce (The Food Institute, 2009). Socio-economic and food environmental factors are playing an increasingly important role in affecting a household’s food choice, along with more traditional measures of demographic impacts. In our study, out of the three factors, food environment trumped socio-economics and demographics.

The effect of context on food choice impacts consumer preference and will continue to shape future food purchase decisions, especially as organic produce transitions from niche product to mainstream food. The U.S. organic produce market has reached a level of maturity that demands new marketing strategies beyond its typical consumer base. The organic attribute is important to producers who could benefit from extracting higher premiums over the conventional good. An understanding of what factors might encourage increased consumption of healthful foods is especially important to producers and marketers for developing more effective marketing strategies. Furthermore, government agencies could build on this information to promote nutritional choices and provide education to encourage consumers to switch from fast food to healthy yet affordable food products.
References


The Nature of Climate Science for the Rocky Mountain West: Implications for Economists Trying to Help Agriculture Adapt

Christopher T. Bastian, Stephen T. Gray, Dannele E. Peck, John P. Ritten, Kristiana M. Hansen, James M. Krall, and Steven I. Paisley

Introduction

Climate change may impact the economic viability of farms, ranches and agricultural communities in multiple ways. Climate change will likely increase evaporation and water loss from plants, thereby increasing drought severity while also creating the potential for more frequent droughts (Karl et al., 2009). Drought impacts in the West will likely be amplified as declines in mountain snowpack affect runoff, water storage, and irrigation. Increased pest outbreaks, disease, and extreme weather will also pose critical challenges for crop and livestock production (Karl et al. 2009).

There have been literally hundreds of papers published on climate change and its potential effects. McCarl (2010) concludes there are still many gaps in the literature related to climate change impacts, climate change adaptation, and climate change mitigation analysis. He notes a need for greater identification of regionalized adaptation strategies and for communicating these strategies to stakeholders through outreach efforts. Similarly, Antle and Capalbo (2010) state that investments must be made to reduce the uncertainty about the value of adaptive alternatives for agriculture. In recognition of these needs, the United States Department of Agriculture’s Agriculture and Food Research Initiative Competitive Grants Program has increased its emphasis on research and related outreach education regarding agriculture and its ability to adapt to, or mitigate, climate change (see http://www.nifa.usda.gov/funding/rfas/afri.html). As agricultural economists increase their research and outreach efforts on climate issues, understanding the nature of climate science as an input into regional and localized economic analyses will be critical if such efforts are going to have a positive impact. The uncertainty associated with the current state of climate science will be particularly challenging for agricultural economists working in the Rocky Mountain West.

Trend Analysis and Modeling Uncertainties

Many previous studies have focused on changes in average conditions over time (see for example Adams, Hurd and Reilly, 1999; Karl et al. 2009). The use of mean conditions originates from approaches adopted by the Intergovernmental Panel on Climate Change (IPCC) that depict climate change as a more-or-less linear trend over the next 50 to 100+ years, or as a snapshot of conditions at some point in the future (e.g., climate averaged over the period from 2040-2060). In many cases these approaches also involve the examination of “ensemble” averages or other summary values intended to capture the consensus of projections. Likewise, IPCC-type assessments and related datasets almost invariably center on climate change at
regional to continental scales. Thus, a focus on ensemble average outcomes at the regional or continental scales may create issues for decision making at finer or more local scales.

Because these coarse-resolution datasets are the most well-known and readily available sources of climate-change related information, many earlier economic analyses have also tended towards a “broad-brush” approach. Economic work building on this IPCC-type spatial and temporal framework has, in turn, offered a great deal of insight into the urgency of many climate change issues, and provided a general sense of how climate change might impact wide geographic areas or large segments of the economy. It is extremely difficult to apply lessons from these assessments at the local spatial or specific enterprise level, which is essential for agricultural adaptation. A broad-brush approach ignores key aspects of climate change and climate variability at finer scales. This general approach presents an overly simplistic picture of the adaptation and mitigation challenges agriculture may face.

The concept of climate change as a linear trend can be useful in some applications. Climate is the sum of myriad interactions between the oceans, atmosphere and land surface, all of which occur over a variety of spatial and temporal scales. These interactions also take place within the context of internal events such as periods of volcanism, and external forces such as changes in solar output. Treating climate change as a trend allows distillation of these factors into key elements, and the resulting visual depictions are often striking and broadly accessible. Moreover, they can provide vital input for broader policy relevant analyses.

Unfortunately, the simple climate trend model neither provides a practical, operationally-relevant portrayal of the future conditions that producers are likely to face nor captures the range of potential changes that producers should expect. First, the simple trend fails to capture climate variability over multi-year to multi-decadal timescales. Numerous studies using actual observations from the past ~150 years and paleo-proxy data (e.g., tree-rings, lake sediments, etc.) stretching back 10,000 or more years show that regional climates tend to fluctuate between predominately wet and dry or predominately cool and warm conditions over periods of roughly 10-60 years (Cook et al. 2004; Gray et al. 2004). At times, the magnitude of these inherent fluctuations can equal or exceed expected changes in mean climate over the next 50-100 years (Figure 1). In the western United States, the resulting drought and wet phases have been a defining feature of regional climates, and the resulting consequences for ecosystems and agriculture have been enormous (McCabe et al. 2008).
Figure 1. Reconstructed Palmer Drought Severity Index values for southeastern Wyoming. The reconstruction is based on tree-rings (Cook et al. 2004), and the values have been smoothed with a 20-year moving average. This 1,000 year record shows marked decadal to multidecadal variability that results in persistent drought (negative values) and wet (positive values) regimes through time.

Such "D2M" (decadal to multidecadal) variability results from a complex set of drivers. Much of this activity originates from processes related to ocean circulation and the associated movement of heat from the equator towards the poles. Given the nature of these processes, the D2M-type variability that has always brought the Rocky Mountain West persistent droughts or periods of frequent flooding is likely to be in operation for the foreseeable future. This means that future climate maybe a blend of significant portions of greenhouse-gas induced trends as well as climate regimes that shift over multi-year or longer periods. This combination expands the potential range of conditions agricultural producers may face (Figure 2). This outcome is important when one considers how inherent variability has the capacity to amplify anthropogenic trends (or vice versa).

Consider a general trend towards increasing summer aridity and inherent D2M variability leading to a major drought-prone phase. The consequences would likely include severe, sustained droughts outside the range of anything in the historical record or most climate-change projections. Conversely, D2M variability that moves toward the wet end of the spectrum for 5, 10 or 15+ years might serve to temporarily mask the overall impacts of broader scale climatic changes.
Further complicating matters is the fact that climate change projections themselves are associated with a tremendous amount of uncertainty. Climate predictions indicate, unequivocally, that the Earth will continue to warm for the foreseeable future (IPPC 2007). However, accurately estimating the rate and magnitude of potential warming at finer scales is exceedingly difficult. Consider the case of southeastern Wyoming. Comparisons between 16 different climate models running under various emissions scenarios, which are impacted by differing population and economic assumptions, yield a 12° F divergence between projections for low- and high-end warming by 2050 (Figure 3).

Ongoing warming will have significant impacts on processes that control storm tracks and other key aspects of precipitation delivery (e.g., El Niño/La Niña). Uncertainties multiply rapidly reducing confidence in the sign of future precipitation changes. Additional heating may alter the frequency and intensity of precipitation, storms and extreme events such as heat waves and cold-air outbreaks (Diffenbaugh et al. 2005; Trapp et al. 2007, 2009). Until models can better resolve storms, cloud formation processes and local land-surface to atmosphere feedbacks, the specifics of these changes remain highly tenuous.
Figure 3. Range of future temperature projections for southeastern Wyoming (after Maurer et al. 2007). Projections are drawn from a set of 16 global circulation models, and results have been downscaled to 4 km resolution. Each model is also run under three different emission scenarios (IPCC 2007), with the B1, A1B and A2 scenarios representing low, medium and high emissions, respectively.

Emissions scenarios—the very foundation of future climate projections—are themselves highly uncertain. The underlying economic, political and demographic factors that control the consumption of fossil fuels are immensely complex and interconnected. At the same time, releases of greenhouse gases from melting permafrost, logging of tropical forests, and other terrestrial sources of carbon are not fully accounted for in these scenarios. Other issues such as the capacity for the world’s oceans to serve as sinks and sources for carbon remain unresolved.

**Rocky Mountain West as a Case Example**

In the early 2000’s coarse-scale general circulation models (GCMs) provided output with a resolution measured in degrees of latitude and longitude. This meant that major topographic features such as the Sierra Nevada and Rocky Mountains were not adequately depicted creating an inability to differentiate between valley bottoms and the high country. Efforts since the IPCC Fourth Assessment Report (2007) have brought some improvements in the resolution...
of GCMs. Recent years have featured major advances in downscaling which is a family of techniques that translates GCM output into finer-resolution projections. These advances include the use of regional scale, process-based models that can be used to better explore the interactions between climate and local topography (e.g., Salathe et al. 2010), as well as, efforts aimed at understanding future climatic extremes such as heat waves or flood-inducing precipitation events (e.g., Rosenberg et al. 2010). As such, downscaling and related research is beginning to provide a glimpse into climate change processes at scales, and of the types, most relevant to producers. However, these techniques do not necessarily improve the accuracy of long-term projections. Downscaling cannot necessarily correct inherent problems in the global models. The potential resulting “multiplication of errors” can lead to additional uncertainty in-and-of itself. While downscaling offers one of the best means for exploring how climate change might play out over “real world” terrain, such processes still have many important limitations. This is especially true for the Rocky Mountain West. Despite these limitations, predictions from these downscaling techniques provide the best available climate forecasts for the region.

While future warming is considered to be virtually certain in the Rocky Mountain West, precipitation projections are still highly uncertain for reasons discussed (Mearns et al. 2005). Median estimates from the 21 climate models used in the IPCC’s (2007) Fourth Assessment Report suggest 2 to 5% increases in winter precipitation over the area while spring and summer precipitation may decrease by 3.5 to 7% by 2050. However, regional downscaling exercises (e.g., Maurer et al. 2007) show that the range on these predictions is very large, with winter wetting sometimes increasing by 10%, and summer conditions ranging from no change to a 15-20% reduction in spring and summer precipitation. A growing number of studies also suggest that climate change may bring increased variability in precipitation that might be manifested as changes in storm frequency and severity (e.g. Trapp et al. 2007), as well as enhanced interseasonal and interannual variability (Leung et al. 2003). Significant model uncertainty remains (IPCC 2007), and the potential magnitude of such changes is likely to vary significantly at the sub-regional level (Trapp et al. 2009). Moreover, this uncertainty in outcomes regarding model predictions and magnitude of change is exacerbated by the potential variability in microclimates across the region. Changes in the amount, timing, frequency and duration of precipitation are likely to have profound implications for agricultural production in the region.

Increasing temperatures will likely bring a suite of consequences for water users in the Rocky Mountain West, including earlier and faster spring runoff, and diminished late-season flows (Stewart et al. 2004). Among these impacts, warmer temperatures could have some of the greatest effects on water supply vulnerability by altering the timing of snowmelt. When compared to historical averages, a clear trend toward earlier spring runoff has already been recorded in the Sierra Nevada Mountains of California, as well as the Cascade ranges in Oregon and Washington (USGS 2005, Stewart et al. 2004). During recent drought years in Wyoming, runoff was earlier and faster in many parts of the state. If early runoff becomes commonplace in the future, storing water for the Rocky Mountain West and downstream users could become more challenging. In short, a rapid or “flashy” runoff could limit the ability of reservoir managers to balance flood control and storage. Moreover, an early runoff inevitably leads to diminished late-season flows, which are crucial to a wide variety of agricultural users, as well as municipal, industrial, and environmental uses.

Increasing temperatures will also bring increased evaporative losses from lakes, streams, wetlands and from terrestrial ecosystems (Arnell 1999). This aspect of climate-change may be especially difficult for water users to cope with because it would occur at the same time agricultural producers require more water for irrigation (Brikowski 2007). Increasing temperatures will also significantly intensify the types of dry events seen in the historical record,
and might even bring about a new type of climate where conditions we previously thought of as “drought” become the norm (Seager et al. 2007).

Implications for Economic Analyses and Outreach Education

Climate change predictions for the Rocky Mountain West indicate potential for increased temperatures, variability in precipitation and irrigation supplies, and frequency in drought events. The variability in these projections relevant to the region is significant. Thus, to be relevant at the finer regional or localized scale, economic analyses will need to incorporate a relevant suite of climate alternatives rather than a predicted “average” scenario as the uncertainty of the average occurring may provide erroneous information for decision making. Climate science scenarios will have to be developed that can provide a broad range of potential outcomes that will define constraints such as water for irrigation, yields, growing seasons, and grazing days. This will be exacerbated by the inability of climate science predictions to provide reasonably accurate probabilities associated with potential outcomes. Thus, agricultural economists will need to further develop techniques being reported in the recent literature designed to capture non-linear trends (see for example Schlenker and Roberts 2006) and/or simulation techniques coupled with stochastic programming (see for example Peck and Adams 2010; Ritten et al. 2010) to capture uncertainty in key parameters or constraints and a range of possible outcomes.

Another challenge facing economists doing such analyses may be a lack of accurate data regarding production responses and economic variables across a broad range of climate scenarios. Crop scientists have been investigating production technologies and new cultivars for the Rocky Mountain West (see for example Krall et al. 2007), but yields for a broad range of climate scenarios may not be well understood. Performance of individual cultivars over a broad range of conditions may be especially important to understand if climate change causes temperatures and precipitation to become more variable (i.e., if extremes become more extreme, not just more frequent).

Adams and Peck (2008) explore the effects of changes in drought frequency versus drought severity. They assume farmers produce the same general suite of crops and simply adjust the proportion of various crops in their rotation as well as their irrigation technologies or management. The authors found more extreme drought (holding frequency constant) was more damaging than more frequent drought (holding severity constant). Thus, understanding how crops may perform under scenarios of increased extreme events may be more important than average events.

Ritten et al. (2010) find that stocking rates and resulting profitability are more impacted by variability in precipitation than changes in mean precipitation. They suggest their study is limited by not addressing the potential change in range forage species composition and quality under climate change. Other issues from climate change could impact livestock performance as well. Less severe winters, for example, could allow disease vectors, such as ticks and parasites (intestinal helminthes), to overwinter more successfully, leading to higher disease rates in livestock. Changes in runoff patterns and or flooding could change mosquito dynamics and influence diseases such as bluetongue and West Nile virus, for example.

Crops might also be impacted by similar disease issues brought on by climate change. Additionally, finding appropriate price data for alternative niche crops or crops new to an area may be difficult. As extreme weather such as long term drought events become more frequent, factor markets for both inputs (for example feed) and outputs related to agricultural production may change, impacting both variability and means of relevant price series for economic models.
Economic models will have to be dynamic. Many possible scenarios will have to be analyzed to capture a relevant range of potential outcomes for agriculture which may include changes in both variability and means of relevant production and economic variables. Analyses will have to be systems oriented to address most potential issues impacting production and economic outcomes. For example, irrigation water availability for crops or spring precipitation for range will likely be impacted. Thus, models relating precipitation or snowpack to resulting irrigation supplies may need to be developed to feed into production or yield models that then feed into economic models.

The ability of agricultural firms to adapt to climate change in a timely fashion is likely complicated by the fact that at local to regional scales, and on time frames of several years, natural climate variations can be relatively large and temporarily mask the progressive nature of global climate change (Karl et al. 2009). This masking of climate change phenomena at the local and regional level is likely coupled with potential skepticism of climate change by many agricultural producers. This will pose an additional challenge as agricultural economists offer regionally relevant outreach education from research that will likely provide an array of potential outcomes. Outreach efforts will have to engage producers as part of an initial assessment of beliefs and concerns regarding climate change as well as relevant alternatives given the broad suite of potential climate predictions at the local level. Thus, once engaged in the process, research results could help producers assess the following:

1) whether or not production strategies and policies in place today would be adequate under a wide range of potential climatic changes;

2) how changing production costs or shifting product demand might interact with climatic variability and change; and

3) how various adaptation strategies might (or might not) be viable across a wide range of potential climatic and economic futures.

This should help agricultural producers decide for themselves how best to adapt given their resources and assessment of potential outcomes for their operations.

References


Modeling Information in Environmental Decision-Making

Craig A. Bond and Terrence Iverson

Introduction

Uncertainty abounds in environmental and resource management problems. There is uncertainty about the physical processes themselves, uncertainty about which physical consequences people care about, and uncertainty about the value of the relevant outcomes. Some uncertainty may be expected to diminish with learning over time, but much will remain beyond the time when decisions have to be made. As a result, decision-makers cannot simply wait for uncertainty to go away. Policy needs to anticipate. Decisions must be made ex ante.

When evaluating choice under uncertainty, most applied work in environmental and resource economics builds on the well-worn structure of expected utility maximization (the EU model) or subjective expected utility maximization (the SEU model). There are good reasons for this. For one, it is easy to use. Linearity in probabilities provides a convenient analytical structure that has enabled economists to prove a wide range of useful results. For example, we can clearly define what we mean by an increase in risk, and we can concisely describe how changes in risk will affect optimal decisions (Rothschild and Stiglitz 1970, Arrow 1971).

A second explanation may ultimately be more satisfying—though we as applied economists rarely discuss it. This is the criterion’s normative rationale. In economics, the presumptive assumption in normative inquiry is that decisions be consistent with how a “rational” decision maker would act. Rationality is then defined by a set of transparent rules, or axioms, that impose forms of consistency on the decision algorithm. A common example is transitivity: if one prefers x to y and y to z then they should also prefer x to z. Axiomatic rationale offers a strong basis for motivating public policy decisions because the unappealing consequences of violated axioms can be made explicit.

The axiomatic foundations for the EU and SEU models were developed by von Neumann and Morgenstern (1944) and Savage (1954), respectively. It is fair to say that they have been widely—though by no means universally—regarded within our profession as compelling. And though a vigorous strand of inquiry has persisted in questioning the canonical model’s justification (for example, Ellsberg 1961 and Kahneman and Tversky 1979), this has not stopped it from becoming the default language for discussing the economics of risk and time. This dominance carries with it the potential for dangerous complacency, especially when policy recommendations follow from potentially misspecified models.

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2 The two models imply the same maximization problem, in which expectations are formed through summing probability-weighted outcomes. They differ in their interpretation of probability—for the EU model, probabilities are objectively given, while for the SEU model, they reflect the decision-maker’s subjective beliefs.
In this paper, we argue that deviations from the simple setting for which the EU/SEU model was originally intended—and for which it is optimally suited—are more common than is often acknowledged. Indeed, common features of many environmental and resource management problems virtually ensure this. As such, we discuss the consequences of an excessive reliance on the EU/SEU paradigm in formulating policy decisions, and we explore some promising options for moving beyond it, as well as suggesting some other avenues of future research. Our intention is not to provide a comprehensive review of available techniques, nor to work out any particular approach in detail. Rather, we strive to provide a context for thinking about modeling informational issues in environmental decision-making, and to encourage additional research. We do this by pointing out specific ways in which structural components of the workhorse stochastic dynamic optimization framework can be extended or relaxed, and provide an invasive species example (zebra and quagga mussels in aquatic environments) to fix ideas. The paper should be viewed as a complement to Shaw and Woodward (2008) who discuss similar, though not identical, issues.

**When the Assumptions Don’t Fit**

The EU/SEU model works best when the information available for decision-making is well behaved in particular ways. Three deviations from the ideal information structure warrant emphasis for environmental policy decisions. They are shown in Figure 1.

1. **Severity of uncertainty** refers to the extent to which uncertainty can be measured or quantified. A low rating implies that existing data is sufficient for decision makers to confidently assign probabilities, while a high rating implies a situation in which probabilities cannot be uniquely assigned. This distinction has a long history in economics dating back to early contributions by Knight (1921) and Keynes (1921).
2. **Importance of tail events** refers to the importance of high consequence, low probability events in expected utility calculations. As Weitzman has recently shown, so-called “fat tail” distributions have the potential to overwhelm expected utility calculations (Weitzman 2009).
3. **Potential for learning** reflects the extent to which future information flows are important for ex ante decisions.

Information structures near the origin in Figure 1 are well behaved in the sense that they offer solid footing for expected utility maximization. In contrast, information structures away from the origin strain the validity of the standard model. Such deviations are important for many environmental and resource management problems because of a common set of physical characteristics that these problems share. These are listed in the first column of Figure 2. Problems that share some or all of these features include climate change mitigation, biodiversity conservation, and invasive species management, just to name a few. The links between these physical characteristics and the information structure dimensions in Figure 1 are numerous. For example, novelty implies a situation where scientific knowledge is preliminary and incomplete and thus increases the severity of uncertainty; a long time horizon magnifies uncertainty from all sources; inertia and irreversibilities interact to determine the importance of waiting to learn; and feedbacks increase the importance of tail events by making it hard to rule out probability distributions with fat tails over extreme events (Weitzman 2009, Nordhaus 2011, Roe and Baker 2007).

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3 Additional examples can be found in virtually every paper cited herein; however, Table 1 in Shaw and Woodward (2008) provides a nice conceptual overview characterizing the size of probabilities and the potential for ambiguity over them.
Thus, the relevant information structure for many environmental and resource management problems may deviate from the origin in one or more dimensions in Figure 1. But so what? What if we use the EU/SEU model anyway?

Most importantly, excessive reliance on the EU/SEU model can lead to bad decisions. Consider first a situation where uncertainty is too severe for decision-makers to justifiably specify a unique probability distribution over contending forecasting models. If they persist in using the standard model anyway, they must choose a distribution from among a variety of plausible alternatives. The chosen policy will then perform well—in the *ex ante* sense of balancing expected costs and expected benefits—provided the chosen distribution turns out to be the most appropriate one. But the same policy may perform terribly under another, equally plausible alternative. By forcing policy evaluation into an inappropriate framework, the decision-maker is in effect committing to analytical blinders that understate the true extent of uncertainty. A Bayesian would aggregate probabilities across models with the variance of the aggregate distribution accounting for the dispersion across model alternatives (Brock et al. 2003), but it may still be too much to ask for decision makers to agree on a unique final distribution. A more natural objective when uncertainty is severe is to seek a policy that is in some sense robust across the range of plausible probability distributions, rather than one that performs optimally under a particular distribution while ignoring the implied risks under each of the others.

The consequence of ignoring “fat tailed” probability distributions can be at least as severe. Weitzman (2009) shows that extreme events in the tail of the relevant probability distributions can make an arbitrarily large (i.e., infinite) contribution to the expected utility objective function.
The important takeaway is that the standard practice of ignoring extreme events—predicated on the fact that it is typically difficult or impossible to assign probabilities over them given available data—could lead to arbitrarily bad decisions. Research to better accommodate information about tail events into decision-making is still in its infancy. Nevertheless, it is clear that situations where fat tails cannot be ruled out—most importantly, situations with novelty and feedbacks—warrant pause and concern.

### Figure 2: Physical Characteristics and Decision Context of Complex Management Problems

Finally, the consequence of ignoring the dynamic nature of scientific information has been widely discussed; nevertheless, it is still often ignored in applied work. Arrow and Fisher (1974) and Henry (1974) first recognized that the appropriately measured opportunity cost for an irreversible investment should include the value of future information. This is because future information has value only if the option to act upon it is preserved. This value is sometimes called the quasi-option value. For environmental problems, the quasi-option value can sometimes go in the opposite direction of what one might expect, leading to lower levels of environmental protection than would be justified without it. This is because investments in abatement equipment—like changes in environmental quality—can themselves be irreversible (see Kolstad 1996 for an example). Alternatively, the value of future information may be so great that aggressive exploitation might be warranted in the short run. The key lesson is that there is a value-of-information margin relevant to management tradeoffs that the standard EU/SEU model ignores.

So far, our discussion of the adverse consequences of inappropriately relying on the EU/SEU model has focused on the claim that it can lead to bad decisions. Two additional criticisms warrant mention. First, because most environmental policy decisions are made by groups of stakeholders—rather than by a single decision maker or by a unified decision-making body—we should ask if the EU/SEU model is useful for guiding decision-making in this context. Consider
the case in which uncertainty is severe, so there are a variety of probability distributions that cannot be ruled out in the face of available evidence. In this case, one might naturally expect stakeholders in high stakes policy decisions to defend the probability distribution that most supports their particular interests or values (Herrick and Sarewicz 2001). But this makes application of the EU/SEU model extremely difficult since it cannot be applied without decision makers agreeing upon a unique distribution. There is a substantial literature that looks at aggregating probabilities across a variety of expert specified distributions, but there is no agreed upon methodology. As such, it may be more appealing to start negotiations from a position that acknowledges that a variety of probability distributions are consistent with the data (see, for example, Lempert et al. 2004 and Iverson 2012).

Finally, one can criticize the machinery of expected utility maximization by taking a behavioral perspective. A behavioral lens asks how realistic agents actually do behave, rather than how an idealized rational agent hypothetically would. Historically, economists have often pushed back on the assertion that public policy decision makers should seek to emulate the common sense logic of the average person (for example, von Neumann and Morgenstern 1944, Savage 1954). After all, they would say, the goal of formal analysis is to facilitate an enlightened perspective that goes beyond heuristic biases. The counter argument is an extension of consumer sovereignty: if people respond to uncertain decisions in a way that conflicts with a particular list of axioms, then policy-makers may want to take these deviations seriously—at the very least, within the democratic process, they may be forced to. Carried further, the goal of maximizing social welfare could be interpreted as saying that the desirability of a particular tradeoff should be evaluated with reference to behavior, not theory.

Behavioral critiques of the EU/SEU model center on two long-standing “paradoxes”—the Ellsberg paradox and the Allais paradox. Ellsberg (Ellsberg 1961) showed that people prefer bets with well-defined odds to bets with unspecified odds even when they get to call the terms of the bet in the latter situation. The finding shows that people are more averse to uncertainty over models then the EU/SEU model would suggest. Allais (Allais 1953) showed that people tend to overweight low-probability high-consequence events relative to what they would under the EU/SEU model. This implies that the EU/SEU model does not accurately describe how people will evaluate risky outcomes when low probability tail events are important. Both paradoxes can be used to justify decision criteria that differ from expected utility maximization.

Some Promising Alternatives

To clarify options for handling difficult information structures, we will focus on a general stochastic dynamic optimization problem written in recursive form using the Bellman equation (Bellman 1957). To keep the discussion concrete, however, we discuss the relevant objects with reference to a specific invasive species problem; namely, the threat of zebra and quagga mussels spreading through Western waterways. As documented in Thomas (2010), these species were introduced to U.S. waters in the 1980’s through transatlantic shipping activities. They spread rapidly through the Great Lakes and the Mississippi River Basin, and they are now widespread in the eastern Midwest and Northeast. More recently, the species have been discovered in some inland lakes in the West. They spread primarily through the transport of recreational watercraft.

We start by defining the standard dynamic programming model as follows:

$$V(s_t) = \max_{u_t} f(u_t, s_t; \alpha) + \delta E_x\left[V(s_{t+1}(u_t, s_t, 0, e_{t+1}))\right].$$  \hspace{1cm} (1)
Here $V(\cdot)$ is the expected net present value of following the optimal control $u_t$ from a point defined by the state variables $s_t$. Instantaneous net benefits of following this control path are given by $f(u_t, s_t; \alpha)$, where $\alpha$ is a parameter vector. Expected future net benefits are defined as $E_{e^{t+1}}[V(s_{t+1}(u_t, s_t, \theta, e_{t+1}))]$, which includes a parameter vector $\theta$ and stochastic error vector $e_{t+1}$. It is calculated as the probability-weighted sum of the continuation value starting from next period’s state $s_{t+1}$. The discount factor is $0 < \delta < 1$.

For our maintained example, we assume that (1) represents an interconnected system of reservoirs in the West under threat of mussel invasion. Each reservoir is represented by an element of the state vector $s_t$ and prevention and control strategies at each reservoir (e.g., boat inspections or physical removal of mussels) comprise elements of the vector $u_t$. Spread is stochastic, and depends on the interaction of habitat suitability and factors like boating that increase the opportunity for invasive species to spread.

We define the “standard” stochastic model (near the origin in Figure 1) by an information regime where the instantaneous benefit function and all parameter vectors are known, state variables at time $t$ are observable in contemporaneous time periods, and the distribution (but not the outcomes) of the stochastic shock vector $e_{t+1}$ is known and defined by $g(e_{t+1})$. The expectation over future outcomes in the Bellman equation is then calculated by

$$\int V(s_{t+1}(u_t, s_t, \theta, e_{t+1})) g(e_{t+1}) e^{t+1}.$$ We further assume that $g(e_{t+1})$ is “standard” in that the probability of tail events are essentially exponentially decreasing as they deviate from the central tendency of the distribution. In the example, these assumptions imply that habitat suitability and spread pressures are known, as are the probabilities of establishment. Furthermore, the state of each reservoir (e.g., the population of mussels in each reservoir) is known at each time $t$. Ex ante, the state in $t+1$ is unknown—though the distribution over possible states is known.

Next, we examine how movements away from the origin in Figure 1 affect applications of this standard framework.

**Severity of Uncertainty**

The severity of uncertainty within a standard stochastic EU problem refers to the treatment of current features and future outcomes. With known parameters, the only unknown in the future is the value of $e_{t+1}$. Possible values are weighted by the known probability distribution $g(e_{t+1})$. For mussels, this implies that the only unknown at time $t$ is the state of the reservoirs in time $t+1$.

This formulation is more general then it might at first appear. In addition to embodying standard stochastic problems, it can also accommodate parametric uncertainty (e.g., a particular forcing parameter in a model of climate change, the level of a particular threshold, the spread of an invasive species) and multiple models of the state transition (e.g., uncertainty over the process generating the state data). Parametric uncertainty could imply that a habitat suitability parameter is not known with certainty, as would be the case in colder reservoirs with low calcium concentrations in high elevation areas. It has long been assumed by scientists that such a water body could not support mussel establishment. Recently, however, this assumption has been questioned due to competing empirical evidence (Thomas, 2010). Multiple models of state
transitions in our example might take the form of competing models of the behavioral response of boaters to various control techniques. For example, competing estimates of the elasticity of substitution between substitute sites may exist.

Given some degree of curvature of the value function, the recognition of parametric uncertainty—which might be some recognition of the fact that the optimizing agent is assumed to “know that s/he doesn’t know”—could affect optimal management through a traditional risk result. But implementation would still entail a reasonably straightforward application of linear weighting by probabilities as in the EU/SEU case. Letting $g(\varepsilon_{t+1}, \theta, \alpha)$ denote the distribution over unknowns, the relevant expectation becomes

$$
\int_{\varepsilon_{t+1}, \theta, \alpha} \delta V(s_{t+1}(u_{t+1}, s_{t+1}, \theta, \varepsilon_{t+1})) g(\varepsilon_{t+1}, \theta, \alpha) d\varepsilon_{t+1} d\theta d\alpha. \tag{2}
$$

The expectation includes uncertainty over the parameters in addition to uncertainty over the stochastic component of the state transitions.

To model behavioral responses, one might also assume that the “objective” probabilities, indicated by $g(\varepsilon_{t+1})$, are transformed through some cognitive process into alternative decision weights, say $\pi(g(\varepsilon_{t+1}))$. Several such weighting schemes have been proposed in the literature. Examples include approaches based on prospect theory and cumulative prospect theory (Khaneman and Tversky, 1979; Tversky and Kahneman, 1992) and the rank-dependent expected utility model (Quiggin, 1982).

For our purposes, the key salient point is that the objective probabilities are transformed by a function $\pi(g(\varepsilon_{t+1}))$. As such, the weights used to form the continuing value of the program on the right-hand side of the Bellman equation are not necessarily linear. Low (high) probability future events may be over (under) weighted, thus altering the calculus in the dynamic program and changing “optimal” management from the perspective of the controlling agent (Wu and Gonzalez, 1996). An excellent example is behavior related to a weather forecast – a 90% chance of rain will likely result in the same action (bringing an umbrella) as a 100% chance (Roberts et al. 2008). Reservoir managers may behave similarly for probability of mussel establishment greater than a certain threshold.

Recently, the notation of non-linear weights has entered the resource valuation literature. This is a particular case of our programming problem where statistical techniques are used to recover relative values of $E[V(s_{t+1}(\bar{u}, s_{t+1}, \theta, \varepsilon_{t+1}))]$ given a described, and not necessarily optimal, control rule $\bar{u}$. Examples that test for departures from EU theory or that explicitly estimate weights include Roberts et al. (2008), Glenk and Colombo (2011), Wielgus, et al.

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4 The degree of curvature is endogenously determined given a specification of instantaneous benefits (preferences) and the state transitions of the system.

5 In several papers, Weitzman (1998, 2010) gives an interpretation of the discount rate as a random variable based on stochastic future returns to capital, and Coury and Dave (2010) show how to incorporate non-exponential discounting into dynamic programming problems.

6 For ease of exposition, we suppress the dimensionality of the integration process, but note that we integrate over all of the unknowns.

7 The reader is referred to Kothiyal, et al. (2011) and Shaw and Woodward (2008) for recent reviews.
This literature finds that recovered decision weights associated with money lotteries tend to be “inverted-S” shaped, while weights on environmental outcomes are linear or “S-shaped.” This can have important implications for willingness to pay/willingness to accept environmental policy outcomes when the outcomes are uncertain (see Figure 3).

Moving farther along the uncertainty axis in Figure 1, ability to consistently weight potential outcomes breaks down. For example, it may be that the weights \( g(\varepsilon_{t+1}) \) or \( \pi(g(\varepsilon_{t+1})) \) are themselves uncertain. Several terms are used in the economics literature to describe uncertainty about probabilities. These include ambiguity, Knightian uncertainty, and deep uncertainty. Two versions of uncertainty about probabilities can be considered: one in which “second-order probabilities” can be applied across a set of contending probability distributions, the other in which multiple distributions are possible but probabilities cannot be assigned across them. The appropriate formulation depends on the context. In the mussels example, a specification without probabilities may be most appropriate for confronting a novel threat whose characteristics in terms of reproduction, damage, and spread are largely unknown.

The Ellsberg paradox suggests that people display aversion to ambiguity above and beyond their standard aversion to risk. A compelling option for modeling ambiguity aversion is the smooth ambiguity model of Klibanoff et al. (2005) and Klibanoff (2009).\(^8\) The smooth ambiguity model transforms our dynamic program as follows:

\[
V(s_t) = \max_{u_t} f(u_t, s_t; \alpha) + \delta \phi^{-1} \left( E_\pi \phi \left( E_{\varepsilon} \left[ V(s_{t+1}(u_t, s_t, \theta, \varepsilon_{t+1})) \right] \right) \right),
\]

(3)

where \( \pi \) are second-order probabilities related to the potential distributions characterizing \( \varepsilon \) and \( \phi(x) \) is a concave function. As in the traditional risk framework, the more concave \( \phi(x) \), the more averse the decision maker is to mean preserving spreads in the second-order probabilities. The smooth ambiguity model is applied to climate policy by Millner et al. (2010).

\(^8\) This specification is attractive here due to the fact that preferences are dynamically consistent and the model has a recursive framework. A non-smooth variant, \( \alpha \) – maximin expected utility, is detailed in Ghirardato, et al. (2004) and Melkonyan (2011), and accounts for a range of “optimism” and “pessimism” on behalf of the decision maker. In fact, maximin expected utility is a limiting case with infinite ambiguity aversion (Klibanoff et al., 2009).
A variety of decision criteria can be considered when probabilities cannot be assigned across a set of probability distributions (i.e., the set of contending forecasting models). In environmental settings, the maximin criterion is most famous because it can be interpreted as implementing a strong version of the precautionary principle. Maximin seeks a policy that is robust to the worst-case distribution. Gilboa and Schmeidler (1989) provide axiomatic foundations for maximin expected utility, a criterion that seeks to maximize expected welfare under the worst-case distribution from a set of possible distributions. Roseta-Palma and Xepapadeas (2004) and Vardas and Xepapadeas (2010) build on recent work in robustness in macroeconomics (Hansen and Sargen 2008) that applies Gilboa and Schmeidler’s criterion in a closed loop dynamic control settings—so-called robust control.

Iverson and Perrings (2012) show that maximin can be interpreted as implementing a strictly precautionary response. These authors also show that minimax regret can be interpreted as implementing a strictly “proportional” response. Minimax regret is an alternative decision criterion that Savage (1954) proposed as providing a more reasonable stand in for maximin. Iverson and Perrings (2012) also define a criterion that flexibly varies the relative weight on the competing concerns defined by precaution and proportionality. The suggested criterion nests policies between the extremes of strict precaution and strict proportionality.

In a related direction, Lempert, Popper, and Bankes (2003) employ a regret-based objective function in developing computational methods for identifying policies that perform in a robust way across a wide range of possible models. Lempert and Schlesinger (2000) argue that robust strategies provide a more solid basis for climate policy decision-making in part because they perform reasonably well (if not optimally) “no matter whose view” of the underlying science proves to be correct.

Potential for Learning

We have assumed that if probability distributions for any of the unknown components of the system exist and are known by the decision-maker, then they do not evolve as future information becomes available. But for many environmental and resource management problems, future learning will substantially reduce future uncertainty. Suppose it is believed initially that calcium levels in high elevation reservoirs are insufficient to support mussel establishment, but then a colony of mussels is found at such a location. It seems logical that both the scientific and management communities would take this information into account when designing control strategies.

The ecological paradigm of adaptive management builds on this perspective. Adaptive management of an ecosystem characterized by structural or other uncertainties is recursively structured so that new information is incorporated after either observation or perturbation of the system. Management approaches are changed following the processing of this information. As such, management is “flexible and adaptive” (Holling and Meffe, 1996), but optimality becomes subjective as beliefs about the potential behavior of the system evolve.

Distinctions are made between passive and active adaptive management. Under passive management, potential future learning is not taken into account at the point of decision making. Said differently, the value of information is assumed to be zero when making tradeoffs. Nevertheless, under passive management, beliefs are updated after each observation.
On the other hand, under active management, the value of information is endogenous, and learning is anticipated by the decision maker. This anticipation results in an internal valuation of the additional benefit of future information, which is taken into account when making management decisions.

Active adaptive management has been modeled by augmenting the standard EU formulation to account for the evolution of beliefs regarding uncertain parameters \((\alpha \text{ and/or } \theta)\) and/or states of the system \(z_t \subseteq s_t\). Using state-space techniques, implicit or explicit state transition equations for the sufficient statistics characterizing the unknown distributions can be developed on the basis of observations about the system, and incorporated into the state space.

For example, consider the case of what might be termed parametric uncertainty with respect to (an) element(s) of the state transition equations. At time \(t\), let \(\phi \subseteq \Theta\) be perceived as random variables characterized by a prior distribution denoted \(h(\phi)\). Perhaps, for example, \(\phi\) are the elasticities of substitution between various reservoirs, and visitation to each reservoir in the system are observed and recorded each year. Using some sort of information processing rule (e.g., using Bayes’ rule), implicit updating equations that define a posterior distribution at time \(t+1\) can be written as \(h_{t+1}(\phi) = p(h(\phi), s_{t+1}(u_t, s_t, \Theta, e_{t+1}))\). Practically, these equations could represent the sufficient statistics of the posterior distribution.

In the passive learning case, the Bellman equation becomes

\[
V(s_t) = \max_{u_t} f(u_t, s_t; \alpha) + \delta E_{s, \theta} \left[ V(s_{t+1}(u_t, s_t, \Theta, e_{t+1})) \right]. \tag{4}
\]

Note here that the second term in (4) is the expectation over both the stochastic process and the (random) parameters of interest, but is evaluated at the current, rather than the future, belief. In other words, in forming the optimal management plan, the decision maker does not anticipate the learning (represented by \(h_{t+1}(\phi)\)) that may happen.

On the other hand, an active rule would endogenize the updating of the distribution, rendering the Bellman equation as

\[
V(s_t, h_t(\phi),) = \max_{u_t} f(u_t, s_t; \alpha) + \delta E_{s, \theta} \left[ V(s_{t+1}(u_t, s_t, \Theta, e_{t+1}), h_{t+1}(h_t(\phi), s_{t+1}(u_t, s_t, \Theta, e_{t+1}))) \right]. \tag{5}
\]

The “states” of the system now include both the physical and belief states. Depending on the circumstances, the agent might find it optimal to deviate from the passive control rule (i.e., to experiment) in order to collect valuable future information about the unknown parameters for use in subsequent management actions. The quantitative effect of such learning is likely problem-specific, but the introduction of the information margin provides a means of augmenting benefit-cost analysis with the potential ex-ante value of information (Bond, 2010). Examples of this type of model in various forms include applications to water and air pollution (Kaplan, et al. 2003; Cunha-e-Sá and Santos, 2008), climate change (Kelly and Kolstad 1999; Lange and Triech, 2008), shallow lakes (Peterson, et al. 2003; Bond and Loomis, 2009), invasive species

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\(^9\) In a particular probabilistic setting, this latter type of model is termed a partially-observable Markov decision problem.
management (Springborn, 2008; Haight and Polasky, 2010), and more general applications in policy (Brock and Carpenter; 2007).

In the case of ambiguity, the Kilbanoff et al. (2009) model provides the recursive framework that can be applied to learning under ambiguity as well as risk. Updating functions could allow for the evolution of beliefs over the first or second order probabilities. Consistent with the parametric uncertainty example, the recursive formulation in this case becomes

$$V(s_t, h_t(\phi), g_t(\pi)) = \max_{u_t} f(u_t, s_t; \alpha) + \delta \phi^{-1} \left( E_{\pi \phi} \left[ V(s_{t+1}, h_{t+1}, g_{t+1}) \right] \right),$$

(6)

where $g_t(\pi)$ represents the prior/posterior beliefs regarding the second-order probabilities and we have suppressed unnecessary notation. Note that in (6), the value function includes both first- and second-order probabilities as states of the system, resulting in a very complicated treatment of information processing and risk/ambiguity preferences.

At this point, a word of caution is in order for practitioners attempting to model learning structures in this manner. In practice, modeling partial observability/parametric uncertainty/ambiguity under learning suffers greatly from the curse of dimensionality, as each sufficient statistic related to a particular distribution must be included in the value function (Millner, et al. 2010). Such problems may also exhibit all manner of undesirable behavior from a computational standpoint (e.g., non-convexities, non-monotonicities, discontinuities, non-convergence to true parameter values, etc...). Given current solution algorithms, this may restrict analysis to “toy models” with low dimensionality or evaluations of sub-optimal, exogenously defined paths (as in $u$ above). As discussed in the conclusions, however, techniques and computational power are expanding, and certain general principles may become apparent through even simple representations.

**Importance of Tail Events**

Previously, we assumed the distributions over future (physical) states of the system $g(\varepsilon_{t+1})$ or over parameter values $h(\phi)$ were “standard” in that they declined exponentially with increased distance from the central tendency of the distribution. This is certainly not the case for all distributions. If tail events are far more likely than that described by a normal distribution, then management decisions and policy would be potentially seriously underweighting extreme events.

Consider the case of severe negative events (e.g., a large increase in temperatures as a result of anthropogenic climate change, causing very significant, potentially society-ending effects), where marginal damages tend to infinity yet there is a positive probability of such an event occurring. Weitzman (2009) argues in his “dismal theorem” that standard economic analysis such as benefit-cost analysis cannot be applied or at least is useless, since the expected utility in such a situation is negative infinity (Nordhaus 2011). Others have argued that this is relevant only under fairly restrictive circumstances, but that the “fat tail” problem is still worthy of consideration, especially in the context of large-scale ecosystem change (Weitzman 2011; Nordhaus 2011; Pindyck 2011).

Fat tails and marginal damage are related to the specification of $g(\varepsilon_{t+1})$ (or, in fact, any of the prior distributions assumed in any of the models) and $f(u_t, s_t; \alpha)$, especially $f_s(u_t, s_t; \alpha)$ and
Essentially, for the implications of the dismal theorem to hold, infinite negative marginal utility/net benefits must be assumed at some point in the state space (Pindyck 2011; Nordhaus 2011). A thin-tailed $g(\varepsilon_{t+1})$ in this case may result in a more stringent control effort (in the case of climate change) than assuming fat tails (Pindyck 2011). The interaction between $f(u_t, s_t; \alpha)$ and $g(\varepsilon_{t+1})$ are how the economic implications of extreme tail events are formed.

However, the fact that finite observational data provides little to no information about the density within tails of distributions complicates matters considerably for the empiricist or modeler who wishes to take these considerations into account (Nordhaus 2011).

**Discussion and Conclusions**

The information structure for many environmental and resource management problems does not necessarily match the assumptions of the standard EU/SEU model. Such anomalies can have important policy implications, especially when managing complex nonlinear ecosystems. The severity of uncertainty across environmental outcomes (what precisely is random, and how this randomness is processed and characterized by economic actors), the intertemporal nature of the information structure (whether learning is anticipated or not), and the importance of tail events (including both the preference assumptions and the distributions assumed for the random components of a model) can all interact to explain seemingly paradoxical behavior. This has been repeatedly confirmed in experimental settings and should at least be given consideration when making environmental policy. An understanding of how various information regimes affect benefits/costs and optimal/sub-optimal policies is crucial to the mission of the applied environmental economist, especially given the nature of many of the problems we consider.

Modeling of such issues can shed light on which assumptions are of significant economic importance and how policy can be structured to take these impacts into account. The environmental and resource economics profession seemingly has much to offer in this line of research. Given our relative expertise in modeling revealed and stated preferences of non-market goods, it seems natural that empiricists could contribute to our understanding of information processing, ambiguity aversion, and the slope of marginal utilities in the presence of multiple environmental threats. Key empirical research frontiers include determining “the shape of the [probability weighting function] if we think it might be nonlinear” (Shaw and Woodward 2008, p. 85), evaluating how agents trade-off environmental outcomes in the face of contrary or missing information, (Pindyck 2011) and developing methods that measure the assimilation and processing of new information.

Structural modelers have relevant expertise to analyze the implications of how agents might behave under differing information structures. This also pertains to the types of problems that are most sensitive to the differences. From the impact of fat tails and the degree of uncertainty about the distribution characterizing random processes and parameters, to optimal management under the threat of uncertain processes possibly including thresholds irreversibilities, to the ideal experimental regime that balances future information and “primary” management goals in an adaptive management setting, many questions remain unanswered.

Modeling environmental and resource decisions under alternative information regimes can help identify the key assumptions that drive results. It may also provide a means of exploring the implications of heterogeneous beliefs across both experts and the public at large. Modeling can also contribute to an understanding of the belief conditions under which a proposed
management or policy path may be preferred to others (Bond 2010). These issues and the models representing them are complex. They may require significant investment in methods and techniques (especially numerical) that can account for non-linearities, non-convexities, and large state spaces that are endemic to these applied problems. While each individual problem may be complex and unique, so-called “toy models” could be used to illustrate common principles and results, much like the grossly simplified theoretical models appearing in virtually every economic textbook.

Progress has been made in the engineering literature with advances in real-time approximation of dynamic systems, especially in robotics and artificial intelligence (see, e.g., Atkeson and Stephens 2008 and references therein, and Rust 1997 and Han et al. 2006 for economic applications). These techniques involve approximations of solutions using computational iteration, partial solutions, simple functional forms, and other techniques that exploit the emerging power of computers to perform repetitive tasks. One lesson to learn from this literature is that despite our disciplinary bias towards simple, elegant, and unambiguous analytical results, there can be considerable insight gained from numerical models and approximations, and that even in economic modeling, “the perfect should not be the enemy of the good” (Voltaire, 1772).

Still, it might be that “there can be no descriptively adequate general theory of risky choice which is rational” (Loomes 2006; Shaw and Woodward 2008). Nevertheless, we would argue that by modeling the various issues raised in this paper, the profession can contribute to a greater understanding of the circumstances under which information regimes in environmental problems are salient features, and thus help resource managers and policy makers make ex ante decisions that are ideally pragmatic, yet behaviorally consistent and normatively sound.

References


The Implications of Surface–Ground Water Hydrology for Optimal Conjunctive Management

Kelly M. Cobourn and Neil F. Crescenti

Introduction

Broadly interpreted, conjunctive management is concerned with the joint regulation of surface and ground water resources. In the Eastern Snake Plain of Idaho, conjunctive management has developed largely as a tool to regulate surface and ground water diversion by agricultural irrigators. The practical upshot of Idaho’s conjunctive management rules is that the state may reduce ground water pumping in order to ensure adequate flows for owners of senior surface water rights. This approach is consistent with established water rights institutions, but was developed without detailed knowledge of the hydrologic relationship between surface and ground water (Cosgrove and Johnson 2004; 2005). Questions remain about the most economically efficient means of allocating surface and ground water across irrigators given the characteristics of the region’s water system (Cosgrove and Johnson 2005; Slaughter 2004).

This article addresses the question: How does the hydraulic relationship between surface and ground water affect the economically optimal allocation of water across surface and ground water irrigators? We present an economic model of optimal conjunctive water management that incorporates different hydraulic relationships between surface and ground water. We then use that model to simulate observed conditions on the Eastern Snake Plain. The results of the simulation analysis demonstrate that optimal conjunctive management differs significantly with the form of the hydraulic relationship between surface and ground water. More generally, the analysis shows that incorporating the characteristics of natural systems into an economic analysis can inform more efficient policy decisions.

Surface and Ground Water Relationships

Whenever a surface water body overlies an aquifer, the two water stocks may be classified, at any point in space and time, as hydraulically disconnected or connected. The key difference between the two regimes is that ground water pumping does not affect the quantity of surface water available in a disconnected system, but reduces surface water availability in a connected system.

In a hydraulically disconnected system, the surface water stock is separated from the aquifer by an unsaturated zone (figure 1a). In this case, water flows from the surface water stock into the

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2 By “optimal management,” we mean the amount of surface and ground water diverted that maximizes aggregate irrigator surplus. We do not consider other management objectives, such as maintenance of minimum flows for hydropower production or environmental services.

3 Whether the surface body is disconnected, connected–losing, or connected–gaining may vary significantly over space and time, shifting across reaches of a river or with precipitation events (Winter 1998).
aquifer. A hydraulically connected system, in contrast, is one in which the water table is sufficiently high in elevation that the surface water body and the aquifer are not separated by an unsaturated zone. In a connected system, the surface water stock may be losing to or gaining from the aquifer. In a losing regime (figure 1b), water flows from the surface water stock into the aquifer; in a gaining regime (figures 1c), water flows from the aquifer into the surface water stock.

![Diagram of hydraulic connectivity](image)

**Figure 1. Hydraulic Connectivity and the Effect of Groundwater Pumping**

Notes: Panels (a)-(c) depict types of hydraulic regimes: (a) disconnected stream-aquifer system; (b) hydraulically connected—losing system; (c) hydraulically connected—gaining system. Panels (d)-(f) depict the potential impact of pumping on a hydraulically connected system with a gaining stream: (d) an undeveloped system; (e) pumping reduces discharge; (f) pumping eliminates discharge, system switches to losing stream. Figures reproduced based on Winter (1998).

In a connected—losing regime, groundwater pumping plays a key role in determining the rate at which water moves from the surface water stock into the aquifer: As pumping increases and the water table falls, the rate of recharge increases, drawing more water out of the surface stock and into the aquifer. In a connected—gaining system, an increase in groundwater pumping reduces the water table, reducing the rate at which water flows from the aquifer back into the surface water stock (figure 1e). Regardless of whether the system is losing or gaining, hydraulic connectivity implies that groundwater pumping reduces surface water supplies, though the mechanism by which that process occurs differs between the two regimes.

**Hydraulic Connectivity in the Economic Literature**

Though connectivity between surface and groundwater stocks is recognized in the scientific literature (Miller et al. 2003), the economic literature predominantly considers water management in the context of disconnected systems. The bulk of the economic literature on

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4 In the extreme, pumping may cause a gaining regime to shift to a losing regime, thereby eliminating discharge from the aquifer into the surface water stock and increasing the rate at which the surface water stock loses water to the aquifer (figure 1f). This situation is not considered in the analysis. We assume that the losing and gaining reaches are perennially losing and gaining, respectively, as is the case in the study region.
optimal water management follows a seminal analysis by Gisser and Sanchez (1980), who examine ground water pumping from an unconfined, renewable aquifer. The basic premise of their analysis is that ground water exhibits some characteristics of a common property resource. Thus, individual ground water pumpers, when left to their own devices (i.e. when operating in a perfectly competitive environment), choose a rate of diversion that does not account for the effect of their pumping on the height of the water table and on their neighbors’ pumping costs. Optimal regulation of ground water pumping addresses these externalities and should, in theory, increase aggregate irrigator welfare. They find that this is not the case, particularly for large aquifers. A number of subsequent studies examine the extent to which this result is driven by the behavioral and hydrologic assumptions of the original analysis.5

A subset of this literature focuses specifically on the returns to optimal management in systems that rely on both surface and ground water. These studies vary substantially in their approach and results. For example, Knapp and Olson (1995) and Tsur and Graham-Tomasi (1991) consider the implications of stochasticity in the surface water supply. The former find little difference in the returns to ground water management when including uncertainty, while the latter present evidence that ground water possesses significant value as a buffer against surface water variability. Despite their differences, analyses in this literature generally share the assumption that surface and ground water resources are hydraulically disconnected.

An exception is a study by Burness and Martin (1988), which explicitly considers a connected–losing hydraulic regime. In this situation, ground water pumping generates an externality for surface water users by decreasing surface water flows (in addition to increasing pumping costs for other ground water users). They demonstrate qualitatively that economic optimality requires that surface water be diverted prior to any ground water pumping and that ground water pumping decreases over time before reaching a steady state. However, they do not compare their result with what would occur in a hydraulically disconnected system, nor do they quantify the difference between the optimal management plan and that in which water users operate in a perfectly competitive environment.

**A Model of Optimal Water Management**

The analysis herein extends the economic literature on optimal water management. We develop a model to quantify the surface and ground water diversions that maximize economic welfare across agricultural irrigators.6 Our analysis differs from the bulk of the literature in two key respects. First, we quantitatively compare the allocation of water across surface and ground water users when the stocks are managed independently and when they are managed conjunctively. Second, we explicitly consider the different types of hydraulic relationships that characterize surface–ground water interaction.

We develop six model variants that differ economically and hydraulically. We present two economic scenarios—one in which surface and ground water are managed independently and one in which they are managed conjunctively—and three hydraulic scenarios. The hydraulic scenarios include a system in which surface and ground water are disconnected, one in which

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6 The basic structure of the model can be adapted to accommodate other users and other management objectives.
they are connected and the surface water body is losing to the aquifer, and one in which they are connected and the surface water body is gaining from the aquifer.

In specifying the model, we consider the simplest functional forms that capture the basic characteristics of the problem. We assume separate linear demand curves for surface and ground water, of the form \( W = a + bP_s \) and \( M = c + dP_G \), respectively.\(^7\) \( W \) denotes surface water diversions, \( M \) denotes ground water pumping, \( P_s \) and \( P_G \) are the per-unit prices of surface and ground water, and \( a \), \( b \), \( c \), and \( d \) are parameters. In each period, the gross benefits associated with surface and ground water use are given by the area below the demand curve. The net benefits of water use are given by the area below the demand curve and above the marginal cost curve for water. We assume that the marginal cost of diverting surface water is effectively zero (Contor et al. 2008). The marginal cost of pumping ground water depends on the elevation of the water table, \( H \). The marginal cost of pumping a unit of ground water is given by \( MC_G = m + nH \) (Gisser and Sanchez 1980). The per-period net benefits of water diversions are

\[
\frac{1}{2b}W^2 - \frac{a}{b}W
\]

for surface water, and

\[
\frac{1}{2d}M^2 - \frac{c}{d}M - (m + nH)M
\]

for ground water.

The first economic scenario considered is that in which the surface and ground water stocks are managed optimally but independently. Optimal management of ground and surface water implies that any externalities between users within a group are internalized, as are any temporal externalities associated with water use. The only remaining externalities are those that arise between ground and surface water users. Specifically, ground water users do not take into account the impact of pumping on the surface water stock and surface water users do not take into account the impact of their diversion decisions on ground water levels. In the second economic scenario, ground and surface water are managed conjunctively to maximize the sum of irrigator surplus across surface and ground water users. Under conjunctive management, any externalities between surface and ground water irrigators are internalized. The objective functions by economic scenario are listed in table 1.

\(^7\) There is little conjunctive use of surface and ground water at the individual level in the study region. Overlap of surface and ground water rights boundaries is on the order of 0.72 percent of all permitted acreage (IDWR 2011). Even if an individual producer owns both ground and surface water rights, by-and-large that water is not being applied to the same fields. Under these circumstances, it is appropriate to model the demand curves for surface and ground water as separate because there is limited opportunity for substitution between water sources.
Table 1. Objective Functions and Constraints by Scenario

Objective Function by Economic Scenario

Scenario (1): Independent Management

Surface Water

\[
\max_{W_t} \int_0^\infty e^{-rt} \left( \frac{1}{2b} W_t^2 - \frac{a}{b} W_t \right) dt
\]

Ground Water

\[
\max_{M_t} \int_0^\infty e^{-rt} \left[ \frac{1}{2d} M_t^2 - \frac{c}{d} M_t - (m + nH_t) M_t \right] dt
\]

Scenario (2): Conjunctive Management

\[
\max_{W_t, M_t} \int_0^\infty e^{-rt} \left[ \frac{1}{2b} W_t^2 - \frac{a}{b} W_t + \frac{1}{2d} M_t^2 - \frac{c}{d} M_t - (m + nH_t) M_t \right] dt
\]

Constraints by Hydraulic Scenario

Scenario (a): Hydraulically Disconnected System

\[
\dot{S} = R_S - \alpha (S - W) + (\gamma - 1) W
\]

\[
\dot{V} = R_V + \alpha (S - W) + \phi W + (\delta - 1) M
\]

Scenario (b): Hydraulically Connected–Losing System

\[
\dot{S} = R_S - \alpha (H) (S - W) + (\gamma - 1) W
\]

\[
\dot{V} = R_V + \alpha (H) (S - W) + \phi W + (\delta - 1) M
\]

Scenario (c): Hydraulically Connected–Gaining System

\[
\dot{S} = R_S + \beta (H) V + (\gamma - 1) W
\]

\[
\dot{V} = R_V - \beta (H) V + \phi W + (\delta - 1) M
\]

Notes: \( \dot{S} = dS/dt \), \( \dot{V} = dV/dt \), and \( V = A \cdot S \cdot H \), where \( A \) and \( S \) are time-invariant parameters.

In addition to the objective functions, we need to specify how irrigator diversions affect the dynamic behavior of the surface water stock, denoted \( S \), and the ground water stock. The ground water stock is denoted \( V \), where \( V = A \cdot S \cdot H \). This is the simple “bathtub” aquifer model in which the total volume of water available for pumping equals the area of the aquifer \( A \) times its storativity \( S \) times the height of the water table above the base of the aquifer \( H \). We assume, as is common in these models, that \( A \) and \( S \) are fixed and that changes in the volume of ground water are due solely to changes in the height of the water table.

We consider ground and surface water dynamics in the context of three hydraulic scenarios. Hydraulic scenario (a) represents a hydraulically disconnected system, scenario (b) represents a connected–losing system, and scenario (c) represents a connected–gaining system. Table 1 specifies the dynamic constraints (equations of motion) for each water stock by hydraulic scenario.

There are several commonalities across hydraulic scenarios. \( R_S \) and \( R_V \) denote exogenous net recharge to the system. In all scenarios, a fixed proportion of water diverted from either source
is consumed by plants. For surface water diversions ($W$), a fixed proportion of excess water applied, given by $\gamma$, flows back into the surface water stock as return flows. The remaining proportion, given by $\phi$, percolates directly into the aquifer. This latter proportion is known as incidental recharge, which has historically accounted for on the order of 60 percent of total recharge to the Eastern Snake Plain Aquifer (DAI 2012). Of water pumped from the aquifer ($M$), the proportion of applied water that is not consumed, given by $\delta$, percolates back into the aquifer.$^8$

The three hydraulic scenarios differ in how water moves between the surface and the ground water stock. In a disconnected system, some proportion of water in the surface water stock, given by $\alpha$, percolates directly into the aquifer. In a connected–losing system, water seeps from the surface stock into the ground water stock, but the rate at which it does so depends on the height of the water table: The rate of recharge is a function of $H$ and is denoted $\alpha(H)$. In a connected–gaining system, water does not move from the surface water stock directly into the aquifer. Rather, water seeps from the aquifer into the surface water stock. The rate at which it does so depends on the height of the water table and is given by $\beta(H)$. In a connected–gaining system, water moves into the aquifer only via exogenous natural recharge and incidental recharge from surface water applications.

**Numerical Simulation Analysis**

For the simulation analysis, we consider three reaches of the Snake River that represent hydraulic scenarios (a)-(c). Based on Kjelstrom (1995) and Johnson et al. (1998), we model the disconnected system after the Lewisville-to-Shelley reach, the connected–losing system after the Heise-to-Lorenzo reach, and the connected–gaining system after the Hagerman-to-King Hill reach (Figure 2). For each scenario, we numerically solve for the optimal steady-state values of surface and ground water diversions. To parameterize the simulations, we draw on Kjelstrom (1995), and derive other parameters based on the state of the system at the time of Kjelstrom’s study. The parameters are reported in table 2 and described briefly here.

$^8$ No excess ground water applied runs off into surface water bodies. We have not found any evidence that return flows from ground water irrigation contribute significantly to surface water flows. This may be the case if fields irrigated with ground water tend to be distant from surface waterways or lack return flow conveyance infrastructure.
It is generally accepted that the most productive ground water in the ESPA is in the upper 500 feet. The aquifer is spread over an area of 10,800 square miles, or 6.912 million acres, and stores a total of 200-300 million acre-feet of water (DAI 2012). Assuming a maximum storage capacity of 300 million acre feet (maf) and a maximum water table height of 500 feet, the implied aquifer storativity coefficient is 0.087.\(^9\) This is within previously estimated bounds for the ESPA (Cosgrove et al. 2006).

\(^9\) We define the height of the water table, \(H\), relative to the base of the aquifer, which we assume is 500 feet below the land surface. For example, an \(H\) of 200 indicates that the water table is 300 feet below the land surface and 200 feet above the bottom of the aquifer.
Table 2. Economic and Hydrologic Assumptions Used in the Simulation Analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Assumptions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>Demand Intercept, SW (acre-feet/year)</td>
<td>300,315</td>
<td>1,791,864</td>
<td>50,521</td>
</tr>
<tr>
<td>b</td>
<td>Demand Slope, SW</td>
<td>-1663.96</td>
<td>-9,928.22</td>
<td>-277.32</td>
</tr>
<tr>
<td>c</td>
<td>Demand Intercept, GW (acre-feet/year)</td>
<td>150,158</td>
<td>895,932</td>
<td>25,026</td>
</tr>
<tr>
<td>d</td>
<td>Demand Slope, GW</td>
<td>-831.98</td>
<td>-4,964.11</td>
<td>-138.66</td>
</tr>
<tr>
<td>m</td>
<td>Marginal Cost Intercept, GW ($/acre-foot)</td>
<td>34.51</td>
<td>34.51</td>
<td>34.51</td>
</tr>
<tr>
<td>n</td>
<td>Marginal Cost Slope, GW</td>
<td>-0.051</td>
<td>-0.051</td>
<td>-0.051</td>
</tr>
<tr>
<td>r</td>
<td>Annual discount rate</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Hydrologic Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rs</td>
<td>Net SW Inflows (acre-feet/year)</td>
<td>523,836</td>
<td>1,638,740</td>
<td>-56,318</td>
</tr>
<tr>
<td>Rv</td>
<td>Net GW Inflows (acre-feet/year)</td>
<td>-198,734</td>
<td>302,251</td>
<td>111,570</td>
</tr>
<tr>
<td>a</td>
<td>Aquifer Area (acres)</td>
<td>262,483</td>
<td>1,566,138</td>
<td>43,747</td>
</tr>
<tr>
<td>s</td>
<td>Aquifer Storativity Coefficient</td>
<td>0.087</td>
<td>0.087</td>
<td>0.087</td>
</tr>
<tr>
<td>γ</td>
<td>SW Return Flows (proportion)</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td>φ</td>
<td>Incidental Recharge (proportion)</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td>δ</td>
<td>GW Return Flows (proportion)</td>
<td>0.250</td>
<td>0.250</td>
<td>0.250</td>
</tr>
<tr>
<td>α</td>
<td>Recharge, Disconnected System (proportion)</td>
<td>0.061</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>h</td>
<td>Recharge Intercept, Connected-Losing System</td>
<td>–</td>
<td>0.093</td>
<td>–</td>
</tr>
<tr>
<td>j</td>
<td>Recharge Slope, Connected-Losing System</td>
<td>–</td>
<td>-0.00019</td>
<td>–</td>
</tr>
<tr>
<td>k</td>
<td>Discharge Intercept, Connected-Gaining System</td>
<td>–</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>l</td>
<td>Discharge Slope, Connected-Gaining System</td>
<td>–</td>
<td>–</td>
<td>0.00020</td>
</tr>
</tbody>
</table>

Notes: (a) indicates the hydraulically disconnected reach (Lewisville-to-Shelley); (b) indicates the hydraulically connected–losing scenario (Heise-to-Lorenzo); (c) indicates the hydraulically connected–gaining scenario (Hagerman-to-King Hill). The symbol – indicates that the parameter is not applicable to that particular model variant. Rs and Rv are interpreted as net inflows into stock in each reach. A net negative value indicates that more water flows out of the reach than in. These two parameters are free calibration parameters that we adjust such that surface water flows, surface diversions, and the ground water table reflect observed values from Kjelstrom (1995) under the independent management scenario.

Approximately 2.5 million acres in the Eastern Snake Plain are irrigated. The bulk of the agricultural land base is in forage crops, wheat, and barley (NASS 2007). Roughly half of the total is in forage, and the remainder is split between wheat and barley. Assuming this crop mix and using the IDEP (Irrigation Water Demand from Evapotranspiration Production Functions) tool, an aggregate water demand curve is estimated for the entire Eastern Snake Plain (Contor 2008). Total water demand is split such that 2/3 of is for surface water and 1/3 is for ground water.
water (Kjelstrom 1995). The IDEP produces non-linear demand curves, to which we take a linear approximation over the range of prices for which the quantity of water demanded is positive (0 to $190 per acre-foot). Given zero marginal cost, the quantity of surface water diverted is the intercept of the surface water demand curve, or 7.9 maf for the region.

We generate a scaling factor for each reach based on reach-level surface water diversions reported by Kjelstrom and a total of 7.9 maf for the region. We use this scaling factor to generate reach-level demand curves for surface and ground water. We also scale the size of the aquifer underneath the river reach. In so doing, we impose the assumption that the manager is considering only surface and ground water diversions in a neighborhood of each reach (where the size of that neighborhood depends on the relative weight of that reach in total surface water use). Of course, water management decisions anywhere on the Eastern Snake Plain will affect water availability throughout the Plain, not just in a neighborhood of a reach. However, the externalities between surface and ground water users are arguably greatest within a neighborhood of a reach, both in quantity and immediacy. Moreover, defining a neighborhood around a reach is consistent with the way in which conjunctive management has been practically implemented to date. Finally, in a region that exhibits heterogeneous hydraulic relationships between surface and ground water, optimal management will likely differ by subregion. The appropriate boundaries or shape of the neighborhood around each reach are an empirical question (Cosgrove and Johnson 2005).

The proportion of applied irrigation water that is consumed via evapotranspiration depends on the efficiency of irrigation technology. We assume widespread use of sprinkler application systems across the region, with average consumption on the order of 75 percent of total applied water. For surface water diversions, the remaining 25 percent is divided equally between return flows ($\gamma = .125$) and incidental aquifer recharge ($\phi = .125$). For ground water pumping, the unconsumed 25 percent percolates back into the aquifer ($\delta = 0.25$).

We use water budget figures from 1980, as presented by Kjelstrom (1995), to characterize surface water flows, irrigator diversions, recharge, and discharge by reach. The Lewisville-to-Shelley reach has 4.58 million acre feet (maf) of inflows and 4 maf of outflows. Of the difference, 0.30 maf are diverted for irrigation and 0.28 maf recharges the aquifer. The scaling factor for the reach is 0.0380 (0.3 of 7.9). In the Heise-to-Lorenzo reach, inflows are 4.75 maf and outflows are 2.84 maf. Of the difference, 1.79 maf is diverted for surface water irrigation, and 0.12 maf recharges the aquifer. The scaling factor for this reach is 0.2266 (1.79 of 7.9). In the Hagerman-to-King Hill reach, inflows total 5.81 maf and outflows total 6.78 maf. Surface water diversions total 0.05 maf and the aquifer replenishes the river in the amount of 1.02 maf. The scaling factor is 0.0063 (0.05 of 7.9).

Based on Kjelstrom’s estimates, recharge in the Lewisville-to-Shelley reach is 6.1 percent of total surface water inflows. Observed recharge in the Heise-to-Lorenzo reach is 2.53 percent of inflows, and discharge in the Hagerman-to-King Hill reach is 17.6 percent of inflows. In the latter

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10 This derivation implies that the crop mix is identical across land irrigated from the two different water sources. This is likely not the case, but the objective is simply to derive an approximate demand curve for the simulation.

11 Specifically, as the distance between a ground water well and the surface water stock increase, the effect of pumping on surface water is attenuated and vice versa (Cosgrove and Johnson 2004; 2005).

12 Several states, such as Oregon, have implemented conjunctive management policies that regulate pumping only within a specific distance from the aquifer (OWRB 2010).
two reaches, the rate of recharge or discharge depends on the height of the water table. With an average depth to water of 136.6 feet in 1980 (based on USGS monitoring well observations across the Plain), the water table height is 363.4 feet above the base of the aquifer. We use this information to estimate linear recharge and discharge functions of the form $\alpha(H) = h + j \cdot H$ and $\beta(H) = k + l \cdot H$. To parameterize these functions, we assume that in a connected–losing reach recharge equals zero when the water table is at its highest, and in a connected–gaining reach discharge equals zero when the water table is at its lowest.

### Results and Discussion

Table 3 presents the results of the numerical simulation by economic and hydraulic scenario. Hydraulic scenario (a) represents a disconnected system. When surface and ground water are managed independently in a disconnected system, surface water users do not consider the impact of their diversion decisions on aquifer recharge. When water is left in the surface water stock, it recharges the aquifer at a rate of 6.1 percent. Any water that is diverted for surface water irrigation does not contribute to direct recharge, but contributes to incidental recharge at a rate of 12.5 percent of the water diverted. Recharge of either type benefits ground water users by increasing the height of the water table. Under conjunctive management, whether it is more beneficial to provide incidental or direct recharge depends on the quantity of surface water diversions demanded relative to the quantity of water moving through the river reach. For this particular reach, it is beneficial to reduce surface water diversions, leaving more surface water in the river. Doing so reduces incidental recharge by 488 acre-feet but increases direct recharge by 3,172 acre-feet. With an increase in net recharge, the ground water table rises as does the optimal amount of ground water pumping.

<table>
<thead>
<tr>
<th>Reach and Scenario</th>
<th>Surface Water $W$ (af)</th>
<th>Ground Water $H$ (af)</th>
<th>$\lambda_S$</th>
<th>$\lambda_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewisville to Shelley Reach (a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Management (1)</td>
<td>300,315</td>
<td>4.580m</td>
<td>0</td>
<td>133,154</td>
</tr>
<tr>
<td>Conjunctive Management (2)</td>
<td>296,410</td>
<td>4.632m</td>
<td>3.4</td>
<td>137,059</td>
</tr>
<tr>
<td>Heise to Lorenzo Reach (b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Management (1)</td>
<td>1.792m</td>
<td>4.750m</td>
<td>0</td>
<td>796,124</td>
</tr>
<tr>
<td>Conjunctive Management (2)</td>
<td>1.785m</td>
<td>5.915m</td>
<td>1.5</td>
<td>803,067</td>
</tr>
<tr>
<td>Buhl to Hagerman Reach (c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Management (1)</td>
<td>50,521</td>
<td>5.866m</td>
<td>0</td>
<td>23,149</td>
</tr>
<tr>
<td>Conjunctive Management (2)</td>
<td>50,575</td>
<td>5.867m</td>
<td>0</td>
<td>22,654</td>
</tr>
</tbody>
</table>

Notes: (a) indicates the hydraulically disconnected scenario; (b) indicates the hydraulically connected–losing scenario; (c) indicates the hydraulically connected–gaining scenario. $\lambda_S$ and $\lambda_H$ are the shadow values for surface and ground water, respectively. af denotes acre-feet per year. All quantities are steady-state values. Those for the independent management scenario are calibrated to reflect conditions in each reach in 1980, based on Kjelstrom (1995) and USGS (2011[a], 2011[b]). The conjunctive management scenario reflects a departure from the observed baseline.

Hydraulic scenario (b) represents a connected–losing reach. The only difference from scenario (a) is that the height of the water table affects the rate of direct recharge. As in scenario (a), surface water use generates an externality for ground water users by influencing the amount of
aquifer recharge. However, ground water pumpers now produce an externality for surface water users: When the water table falls, the rate of recharge from the surface water stock increases, reducing the amount of water available for surface diversions. The simulation results are qualitatively similar to those of scenario (a): It is optimal to reduce surface water diversions, which increases net recharge and the height of the water table, and increase ground water pumping.

Hydraulic scenario (c) represents a connected–gaining reach. The externalities generated by one group for another differ substantially in this scenario, relative to the other two. Surface water diversions affect ground water users via their effect on incidental recharge, but there is no direct recharge from the surface water stock. Ground water pumping generates a negative externality for surface water users: As the ground water table falls, discharge decreases, reducing the amount of water in the surface stock. In this reach, it is economically optimal to reduce ground water pumping. There is a slight increase in the size of the surface water stock and in the height of the ground water table. The change in surface water diversions increases total surface water use over the maximum quantity demanded. This is driven by the assumption that the only way to increase aquifer recharge is by augmenting incidental recharge. It is more appropriate to think of this excess as representing artificial recharge, instead of additional crop applications.

Table 3 also reports shadow values for the surface and ground water stock, $\lambda_S$ and $\lambda_H$, under each management scenario. These values represent the increase in irrigator profit associated with a one-unit increase in the relevant water stock (an acre-foot for surface water and a foot of elevation for ground water). The shadow value for surface water is zero under independent management because surface water users already divert the maximum quantity demanded (the constraint on surface water availability is non-binding). Under conjunctive management, the shadow value represents the change in profit across all water users from an increase in one of the water stocks. In all but one case, the shadow values increase under conjunctive management. The increase in $\lambda_H$ reflects a decrease in the marginal cost of ground water pumping in all scenarios, but also captures the value of a unit of ground water in influencing the surface water stock in scenarios (b) and (c).

The results reported for the independent management scenario in Table 3 replicate observations by reach, as reported by Kjelstrom (1995). The change in water use and stock levels under the conjunctive management scenario represent the optimal direction of change when the two resources are jointly managed. As a basis of comparison for our results, we consider the change in water rights allocations across the Eastern Snake Plain between 1980 and 2008. Based on total permitted diversion limits for all irrigation water rights in the region, surface water diversion limits were relatively constant (they increased by 0.07 percent), while ground water rights allocations increased by 10.7 percent. For ground water, the results differ across the Plain: In the Magic Valley, where reach (c) is located, ground water rights increased by 6.5 percent; in the eastern portion of the Plain where reaches (a) and (b) are located, ground water rights allocations increased by 11.4 percent. For ground water, the results differ across the Plain: In the Magic Valley, where reach (c) is located, ground water rights increased by 6.5 percent; in the eastern portion of the Plain where reaches (a) and (b) are located, ground water rights allocations increased by 11.4 percent. The simulation results suggest that a decrease in ground water pumping is optimal in reach (c), while the optimal increase in pumping in reaches (a) and (b) is on the order of 0.87 to 2.9 percent. While the relative magnitude of permit changes reflects these differences to some degree (i.e. the increase in the Magic Valley is lower than that in other areas), this comparison suggests that the growth in institutional constraints has exceeded the optimal change in diversions under conjunctive management.
Conclusion

This article addresses the design of a conjunctive management system that maximizes the combined welfare of surface and ground water irrigators. The analysis considers different hydraulic relationships between surface and ground water, highlighting a number of externalities that may arise in any system that relies on surface and ground water resources. Considering these externalities is essential in determining the economically efficient allocation of water across users. We show that under some circumstances it may be optimal to reduce surface water diversions and increase ground water pumping. It is therefore possible that the optimal allocation of water across irrigators may conflict with the rules established under existing water management institutions.

However, there are a couple of caveats to this conclusion. First, we do not explore the degree to which these results are sensitive to the parameters used in the analysis. Second, examining each river reach in isolation does not capture the full spectrum of externalities between surface and ground water users. Each reach is tied to other reaches and to pumping in other areas of the Plain. However, looking at individual reaches, as we do here, allows us to isolate the externalities produced by ground and surface water users in each type of hydraulic system. If we were to examine a system that exhibits all three of these scenarios, whether optimal conjunctive management involves reducing surface diversions or ground water pumping depends on the relative strength of each of the externalities discussed.

Perhaps a stronger argument to be made on the basis of the results presented is simply that optimal management differs with the form of the relationship between surface and ground water. Any management system that does not consider the characteristics of the natural system may introduce economic inefficiencies. Such a management system may negatively impact those users who depend on the resources in question. A logical question that arises from this analysis is whether institutions are flexible enough to accommodate different hydrologic conditions. The answer to that question will differ state-to-state across the West. Given recent attention to conjunctive management in Idaho, Oregon, Kansas, Nebraska, and Colorado, for example, the concerns raised in this analysis are likely to become increasingly important for policymakers.

References


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