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Assessing Measures of Drought Impact and Vulnerability in the Intermountain West

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Western Water Assessment

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Introduction

Of the most costly natural hazards for which federal, state and local planners must prepare (like earthquakes, hurricanes, and floods), the impacts of drought have been the least well measured. Valid and reliable measures exist for the meteorological, climatological and hydrological characteristics of drought, but the simple fact that droughts do not cause fatalities or property damages in ways similar to earthquakes, hurricanes and floods, means that we do not have a consistent record of socio-economic impacts at the community, state or national scale, and we cannot readily analyze trends in drought impacts over time as done for hazards like floods and hurricanes (e.g., Downton, et al., 2005; Pielke et al. 2008). Droughts are often included in studies that find growing losses from atmospheric or climate hazards (Changnon, et al., 2000), but their contribution to rising hazard impacts remains unspecified.

Yet drought vulnerability and impacts drive drought response policy, and the new Colorado Drought Hazard Mitigation Plan (Colorado Water Conservation Board, 2010) makes a concerted effort to assess vulnerability while recognizing the difficulties of measuring impacts and vulnerability in consistent and comparable ways. Many gaps exist in our ability to assess and project drought vulnerability; among the findings offered in the Colorado Plan vulnerability assessment are (selected from Annex B, chapters 1-11):

- In many cases vulnerability data is not available consistently statewide.
- Significant data gathering and additional monitoring is required to spatially characterize social vulnerability.
- The Agriculture Sector is large and diverse, and would benefit from a more specific analysis.
- Although systematic documentation is lacking, the impacts to protected areas and ecosystems can be severe and in some cases irreversible.
- Monitoring resources are limited and comprehensive impact information even for the most recent drought is not available.
- While the need for additional monitoring and impact measurement is great, previous studies should not be overlooked. There is a huge amount of data available for Colorado that may be usable given additional analysis with respect to drought.

Indeed, each of the sector assessments (agriculture, environment, recreation, socio-economic, state assets, and municipal water), finds weaknesses in our ability to judge vulnerability and impacts. In agriculture, for example, more analysis is called for on irrigated crops (most attention has been on dryland crops which are, *ipso facto*, more sensitive to drought) and better data is needed to measure the effects of livestock sales during droughts. Very little is known about drought impacts in the expanding ”green industry” including landscaping and related economic activities. Data are also lacking to assess vulnerability of state-owned assets like parks and other lands, dams, ditches and water rights, as well a state-managed resources like fish and wildlife (Colorado Water Conservation Board, 2010 Annex B, Chapter 5, pp. 71- 73).

In this paper we first further explore concepts and literature on drought impacts and vulnerability, and review the literature on the drought hazard. We then assess a suite of impacts indicators that could reflect impacts as well as changes in vulnerability over time, focusing on

Colorado and sectors included in the Colorado Drought Hazard Mitigation Plan (Colorado Water Conservation Board, 2010) and extending parts of the analysis to Utah and Wyoming. We offer some initial attempts to formulate quantitative impacts indicators in selected sectors, testing measures that include, for example, agricultural production, crop insurance payments, urban water supply restrictions, wildfire, and local economic impacts.

Part 1: Drought Impacts and Vulnerability

In addition to the revised state drought plan, this study was also inspired by the conclusion of an analysis of the impacts of the 2002 drought in Colorado by Pielke Sr. et al. (2005):

> *The magnification of the impacts, therefore, with respect to the actual precipitation deficit indicates Colorado society is now more vulnerable to short-term drought than in the past.* (p. 1478, italics in original).

Pielke Sr. et al. offered a detailed analysis of the hydro-meteorological impacts of the 2002 drought, but given the difficulty of quantifying socio-economic effects of drought they offered only generalized impacts drawn from "reports by media and public figures" about urban water restrictions, "irrigation water running out", crop failure, and "ranchers selling all or parts of their herds". Their paper offers two major conclusions about drought impacts in Colorado:

1. there has been a "magnification" of the effects of a given precipitation deficit on streamflow and reservoir storage;

2. Colorado is more vulnerable to the various socio-economic ramifications of drought's bio-physical impacts than in the past.

The first conclusion is revealed in the precipitation, snowpack, runoff, reservoir, and tree-ring data they analyzed, while the second is based on the authors' judgment of qualitative reports and news coverage of the drought. These hypotheses can be re-phrased as:

H_1: "a given precipitation deficit has a growing impact on water resource availability" and

H_2: "a given water resource deficit has a growing socio-economic impact."

Both of these propositions imply a complex train of effects, and possible intervening variables (Fig. 1a), as the authors point out for bio-physical impacts (e.g., a given spring snowpack might yield less runoff if warmer temperatures cause more sublimation and evaporation of the snowpack). We would add to this that a given runoff deficit might reduce water resource availability for a given use (e.g., irrigating crops or landscaping, recreation, or household and industrial uses) more or less depending on another set of intervening variables, such as reservoir storage or alternative supplies (e.g., groundwater) (Figure 1b).

In some cases conservation (or alternative supply) in one use (e.g., crop irrigation) can provide additional supply for another use (e.g., household) if sharing agreements and infrastructure are in place (Figure 1c). But such effects raise the challenge of defining impacts and adaptations in a way that logically reflects the social costs of drought. As long argued in climate impacts studies, an impact can be reduced by adaptive response. But the costs of adaptation must also be considered, and some climate impact studies formulate something like a "net impact" which is the sum of the costs of mitigating impacts via adaptations, plus the un-mitigated impacts, if any (e.g., Adger et al., 2009). In this vein, it makes sense, in the spirit of Pielke Sr. et al., to count conservation, especially mandatory use restrictions, as impacts that reflect society's drought vulnerability, rather than adaptive capacity. Indeed, in the short-run, both physical shortages and conservation (Figure 1b) imply reduced production of, for example, irrigated crops, the pleasures of a green lawn, recreation, or manufactured goods, and, ultimately overall domestic production and wealth. But longer-term adaptations (e.g., alternative crops, snowmaking, or xeriscaping) might ameliorate those direct impacts (Figure 1c), by providing alternative water, achieving desired productivity with less water, or switching to alternative economic opportunities, which, in the long term, could yield lower vulnerability (i.e., lower adaptive costs or reduced un-mitigated loss per unit of drought magnitude, or both).

Poorly Assessed Impacts and a Limited Research Base

Though often subtle, the meteorological and climatological manifestations of drought are relatively well defined and measured (Mishra and Singh, 2010). It is the complex interaction of physical drought and social systems makes it difficult to isolate and measure definitive socio-economic impacts, especially given drought's diffuse and chronic, vs. acute, effects. Drought impacts are difficult to measure in gross or proportionate terms compared to other extreme geo-physical events for several reasons:

- No central database exists for drought losses, with no accepted time series of losses
- Losses generally not manifest in injuries, fatalities or obvious property damage
- Little insurance impact or data (outside of agriculture)
- Few "disaster" declarations
- No unified roster of drought events (like the landfalling hurricane record)
- Difficult to define spatially (area affected) and temporally (beginning and end).

Drought is diffuse in time and space, slow of onset, and of long duration compared to most traditional natural hazards (Burton, Kates and White, 1978; Fontaine and Steinemann , 2009). Droughts do create some obvious and direct impacts (wilted crops, reduced streamflows, brown lawns) and have occasionally evoked local and state "disaster" declarations (as in Atlanta in 1988, and 2005; California 1976-77 and subsequent years), and have even risen to the level of national emergencies (e.g., the 1930s "dust bowl", and 1988 drought; Riebsame et al., 1992). And drought planning, based on vulnerability and coping capacity across sectors and geography, is conducted by many government agencies and many states have drought plans, most of which include some form of assessment and thresholds for drought response (Wilhite, et al., 1987).

Perhaps because of its chronic, rather than acute, character, the drought hazard has been subject to less research and publication, especially in terms of socio-economic impacts (a much larger literature exists on the climatological aspects of drought). The first significant impact studies began with a few early assessments (Warrick, 1975; Rosenberg, 1978), case studies (Riebsame et al. 1991; Dziegielewski et al., 1993), and prescriptive approaches to drought planning and management (Wilhite et al., 1987), with particular attention to triggers for drought emergencies (Hrezo, et al., 1986). The work on triggers and responses aimed at improving drought contingency plans has continued (Steinemann and Cavalcanti, 2006; Dupigny-Giroux, 2001), and most local and state drought emergency plans now include specific, customized response thresholds.

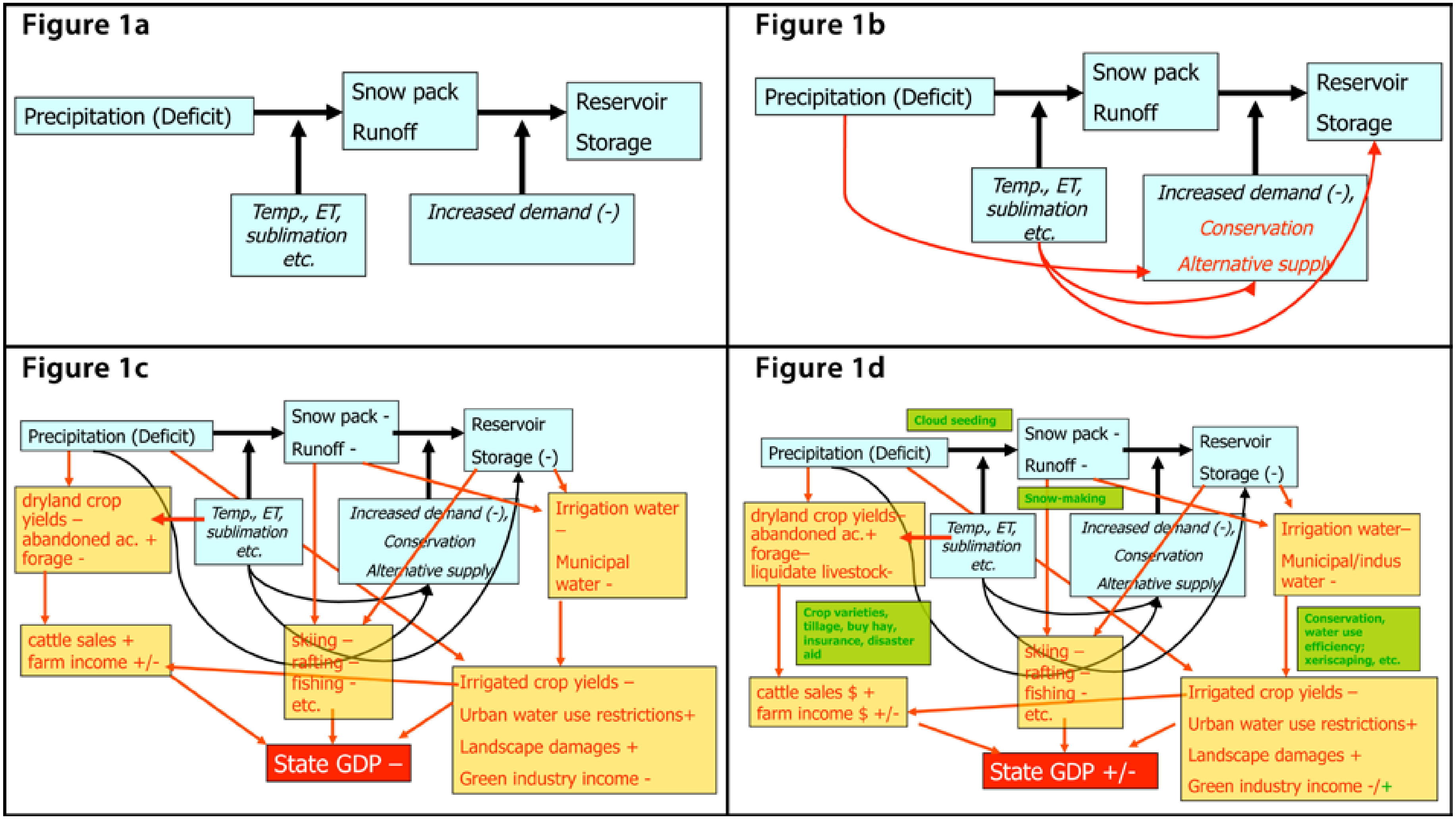

Figure 1. (a) A simple drought impact model as inferred from Pielke Sr. et al. (2007). (b) Added alternative impact pathways, such as precipitation affecting conservation or alternative supplies directly. (c) Economic impacts (red arrows) on various sectors and activities (+/-), including, for example, direct effect of precipitation deficit on dryland crop yields and effects of snowpack deficit on recreation, and ultimate outcome in state GDP. (d) Potential adaptations (green boxes) in agriculture, recreation, and urban water management to ameliorate drought impacts.

A large and still growing historical literature focuses on the 1930s and 1950s droughts in the U.S. (e.g., Worster, 1979), and each significant regional or national drought since the 1960s Northeast drought has occasioned a large gray literature of drought reports (e.g., Dziegieleski, et al., 1993) and occasional book-length treatments (Russell et al. 1970). But very few studies have attempted to measure or track drought impacts and vulnerabilities over time. Bowden et al. (1981) tracked agricultural impacts (yields, foreclosures, and population changes) of major droughts on the U.S. Great Plains (e.g., 1890s, 1910s, 1930s, 1950s, 1970s), concluding that, overall, both physical impacts (e.g., yield declines) and social effects (e.g., farm economic stress), had lessened across these events due to various types of adaptations. On the other hand, in furtherance of their argument that the Great Plains was becoming less sustainable overall, Popper and Popper (1989) argued that late-1980s drought conditions were worse than the 1930s Dust Bowl in terms of soil erosion and farm loss, though they did not offer data to support their claim of increasing vulnerability. Riebsame et al (1991) made a detailed study of the 1988 drought in the US (roughly 1986-89), concluding that its impacts varied greatly across sectors. Agricultural impacts appeared to have been ameliorated by economic supports; for example, even though crop yields were dramatically reduced in the northern Great plains, they found that farmers emerged from the 1988 drought in better financial shape (measured by debt to asset ratio), chiefly because of federal relief and insurance systems. Alternatively, the drought impacts and costs in urban supply (Atlanta), transportation (barge traffic on the Missouri/Mississippi), and ecosystem (wildfires in Yellowstone) increased markedly. Looking back at the 1960s and 1970s drought in the urban Northeast, Russell et al. (1970) found increasing vulnerability defined especially by reduced ratios of ground water safe yield to demand. Instead, each notable drought is studied in isolation (for example: Atalanta, see: South Carolina, see: Knutson and Hayes, 2001). More recent studies tend to generate long rosters of drought impacts and responses (as evidenced in many state drought mitigation plans, based on a template required by the Federal Emergency Management Agency), but rather perfunctory vulnerability assessment, and no longitudinal analysis.

Drought Hazard Trends

There is a strong popular perception that weather and climate hazards are worsening in the U.S. Yet quite a debate has emerged about this topic: Are increasing weather and climate disaster losses due to greater exposure (more people and property at risk), increasing vulnerability (the tendency for loss from a given event to increase as a proportion of exposure), increased frequency and/or intensity of the physical events, and/or some of all of these factors (Changnon, et al., 2000)? Can we even judge these trends with the impacts record available to us?

In short, increasing hazard losses can be caused by:

1. Increased physical hazardousness (e.g., increasing intensity, frequency, and/or duration of extreme events)
2. Increasing reporting and observation, or some other form of measurement bias.
3. Increasing exposure of people and property
4. Increasing vulnerability of people and property (e.g., tendency to incur loss per unit of hazard magnitude per unit of exposure)

A recent assessment of climate change in the U.S. suggests that heavy rainfall events might have increased in the northern states, but otherwise finds no convincing evidence yet of significant trends in extremes over recent decades (while losses increased), especially trends big enough to account for the growing property losses (CCSP, 2009). But even increasing real losses might not mean increased vulnerability as defined here. When U.S. flood and hurricane damage time series are normalized not only by inflation but by the value of property at risk, they flatten out (Downton, et al., 2005; Pielke et al. 2008), suggesting that the dominant driver of increased loss is increased exposure and/or vulnerability. Though the terms *exposure* and *vulnerability* are often used interchangeably, even in technical studies, we think it is important to define and consider them separately, especially since, in a world of expanding human development, any signal of successful hazard mitigation is likely to show up not as decreased exposure (total development subject to hazard impact), and maybe not even as decreased total losses, but as reduced vulnerability (proportion of exposed development likely to be damaged). The proportion of property damaged at a given event magnitude might remain the same (or even decline, if mitigation efforts are effective), but loss could still increase due to increasing total exposure. If seismic design is successfully included in building codes, then simple exposure (e.g., measured by units or building volume subject to earthquake shaking) might increase while vulnerability (proportionate loss) could decrease, or, at least, not increase as fast as exposure, while total losses, even normalized by shaking intensity, might still increase.

It does seem *prima facie* that claims that society is "becoming more vulnerable" to X (e.g., drought), do not necessarily imply that X is increasing in frequency and magnitude (though that may also be happening), rather the claim tends to mean that impacts are increasing for an occurrence of X of a certain magnitude (e.g., drought of a certain intensity and duration). This notion reflects one of the most intuitive and useful definitions of vulnerability: physical and/or socio-economic impacts per unit of hazard magnitude.

Increasing Impact, Exposure, Vulnerability, or all of the above?

As with other hazards, there is a growing perception that droughts are worsening in the U.S., presumably due to global warming (Gertner, 2007). It seems that drought exposure, impacts and vulnerability are all increasing, at the national and regional scales in the U.S. Drought experiences in California (e.g., Dziegielewski et al., 1993) and the Southeast, especially in the Atlanta metropolitan area, were cited in the 1990s as demonstrating growing drought impacts (Wilhite, 1993). More recent droughts have furthered this perception (Pielke Sr., et al., 2008). But the problem of measuring and attributing natural hazard loss trends especially applies to drought since we do not have a consistent drought loss record. Certainly some exposure to drought is increasing: more people are hooked up to more water supply systems. Agricultural production has increased, as has the total insured crop. Urban exposure certainly has increased and, at least in some places and in some studies, there is evidence for increased impact and maybe vulnerability, depending on how it is defined (Hill and Polsky, 2007). But many municipalities have expanded storage and purchased new supplies (especially, in the West, from agriculture). Despite this, farmland has been stable, or declined only slightly, in recent decades (e.g., on the drought-prone Great Plains; see: Parton, et al., 2007), so total agricultural land exposed to drought is not increasing, though more production per unit of land would still imply greater exposure of agricultural production.

To assess whether impacts have been magnified and that society is now more vulnerable, would require an effort to define vulnerability, measure it, and then to come to a conclusion about its trend. One theme in drought discourse in the West, and in Colorado, is that impacts must be increasing simply because more people are using more water. Obviously, vulnerability to drought increases if it is defined as the number of people affected by drought, but in our terminology that is simple exposure, and not a very interesting or telling finding. If only one person lived on the Front Range and another moved in, then vulnerability doubled! The more meaningful definition of vulnerability is proportionate or relative loss, especially compared to exposure, and, ultimately, compared to the economic benefits of resource use. So, the key questions following on Pielke Sr. et al. (2008) become:

> Did we incur losses from the 2002 drought that were a larger proportion of the investment at risk than in past droughts? Were losses a bigger portion of overall economic activity?

We cannot fully answer these questions in this study, but can sort out some of the impact indicators that can be tracked over time to start to illuminate such trends.

Measuring Drought

As with most impact studies we first need a measure of the physical event, and, fortunately drought has been subject to extensive climatological analysis aimed precisely at tracking its magnitude over time with consistent measures or indices. In short, "droughts" are the intense sub-population of dry spells that naturally occur in the precipitation series of a place. Droughts can be characterized by intensity (how dry is it?), duration, and areal extent. In practice, droughts tend to be identified as multi-month to multi-year episodes of abnormal dryness, sometime interrupted by brief rebounds to normal or even above normal moisture.

Two measures of physical drought are well-known and widely used: the Standardized Precipitation Index (precipitation deficit) and the Palmer Drought Severity Index (PDSI), with the PDSI sometimes broken down to its sub-routines for soil moisture (sometimes referred to as the crop moisture index) and surface and ground water (the Palmer Hydrological Drought Index; see: Mishra and Singh 2010).

Given the importance of surface water in the West, and the fact that most of the region's surface supply comes from snow accumulated in higher terrain during the cold months, running off during the warm months often to be stored in large reservoirs, regional climatologists have augmented the typical precipitation deficit measures (like the SPI and PDSI) with measures explicitly focused on water resources. The Surface Water Supply Index (SWSI) was originally developed in Colorado to complement the PDSI with an index reflecting water supply outcomes in areas dominated by snowpack runoff; it is now used in many western states (Shafer and Dezman, 1982; see also Doeskin et al., 1991a and b).

The Colorado Climate Center (CCC) has also calculated the PDSI for smaller geographical units reflecting the state's varied topography, and they continue to refine applications of the SPI, PDSI and SWSI. Indeed, for the 2010 up-date of the Colorado Drought Hazard Mitigation Plan, the CCC re-assessed all three measures and concluded that they each serve as useful impact indicators, the SPI for short-term effects and prognosis, the PDSI for longer-term impacts, including dryland crop losses and streamflow, and the SWSI for water supply and irrigation (Colorado Water Conservation Board, 2010, Appendix E). They use this analysis to recommend mixes of indicators for thresholds of actions under the response plan (Colorado Water Conservation Board, 2010).

But, while the atmospheric and hydrologic drought is well measured, the relationship between such measures and impacts such as on agricultural production, urban water supply, and other sectors is only very roughly correlated. It makes sense that when the various drought measures indicate intense and prolonged drought that greater impacts would be experienced, but, as we show later, the correlation between drought measures and impacts is poor. Moreover, few attempts have been made to correlated drought measures with impact measures except in the roughest ways. In a recent presentation, Colorado's State Climatologist noted that efforts to link improved drought indices like the SWSI to impacts and vulnerability remain to be done. He noted that the Water Availability Task Force has long:

> .... intended to test SWSI by comparing it to observed drought impacts - don't think we ever did that, but always perceived it to be practical and useful. (Doeskin, no date).

The CCC made some progress along these lines in the 2010 up-date of the Colorado drought mitigation plan, linking, for example, PDSI to crop yields and SWSI to streamflow, but the next step, following such bio-physical impacts into the economy, remains to be taken.

In their analysis of drought indices, the CCC also tested monthly PDSI against dryland wheat yields and streamflows for specific areas, indicating which index months best correlate with these measures, but also recognizing that the PDSI tends to reflect longer-term drought. Given its performance for dryland crop yield we here also focus on that link, but also make an attempt to test link between drought and irrigated crops, as recommended in the Colorado drought plan.

Part 2: Toward a Drought Impacts Indicator Suite

Drought Episodes

To strengthen the impact signal, we compare impacts for significant drought episodes across time, and try to define drought episodes in ways similar to how McKee, Doesken and others at the CCC have done (e.g., McKee et al., 2000; see also: Henz et al., 2004) (Table 1).

Drought Period	Worst Years	Characteristics
1898-1904	1902-1904	southwestern
1930-1940	1931-1934, 1939	widespread
1950-1956	1950, 1954-1956	Worst than 1930s in SE
1974-1978	1976-1977	Worst in mountains with record low snowpack
1980-1981		Marked winter drought
2000-2003	2002	Statewide, but especially extreme on Front Range

Table 1. Significant Colorado drought episodes of 20th and 21st centuries, derived from: McKee et al., 2000 and Henz et al., 2004.

As a first cut, and in order to examine impacts of general dryness as well as water resources shortages (which for some analyses may be better defined via the SWSI), we used the

CCC Colorado drought episodes, matched to the PDSI record for the state and for individual climate divisions (the CCC has also established a higher-resolution modified PDSI record for Colorado, which we do not use here because we wished to treat WY and UT in the same fashion). We defined drought episodes as periods of PDSI of -1.00 or less that lasted at least three months. This yields up to 6 major droughts in several of Colorado's climate divisions (example for CD 1 in Table 2).

Drought Period	Run-Sum	Starting Month	Avg. Wheat Field	Best-Fit Line Value	Yield Depression	Depression / Best-Fit
1949-1957	230.31	August	9.81	14.2	4.39	31%
1931-1937	220.53	July	7.05	13.2	6.15	47%
2001-2004	114.36	August	23.19	28.0	4.81	17%
1962-1965	93.09	February	10.70	16.8	6.10	36%
1974-1978	60.6	March	17.65	20.2	2.55	13%

Table 2. Cumulative monthly PDSI (run-sum) and wheat yield departures, Colorado Climate Division 1.

Agricultural Indicators

Following Figure 1, our agricultural indicators includes obvious drought impacts: depressed crop yields and/or production (dryland and irrigated), abandoned crop acreage, livestock liquidation, and agricultural insurance payments. Applying our general approach, we collected annual time-series for these data in CO, WY and UT, and related them to major drought episodes, looking for correlated effects and attempting to compare them over drought episodes and to non-drought periods.

Crop Yields

We follow the example of the Colorado Drought Mitigation Plan's Vulnerability Assessment (State of Colorado, 2010) and examine crop yields separately for dryland crops (sensitive to local precipitation and temperature) and irrigated crops (sensitive to managed surface and ground water resources, and thus not necessarily indicative of local drought conditions). To calculate yield depressions we followed a tradition in statistical crop yield modeling of fitting a polynomial curve to the historical yield (per harvested acre) record to define the "expected" yield. In crop modeling, as in this study, such a trend line is assumed to reflect technological inputs like fertilizer, crop varieties, tillage practices, and other time-transgressive trends that increase yield. Any climate trend operating at this time scale could also be picked up by the polynomial fit, but, as in crop modeling, we are interested in the inter-annual variation of yields, not their long-term trend. Inter-annual variations, assumed to derive chiefly from climate conditions, can of course also be affected by pests and other impacts, as well as short-term changes in technological inputs or other treatments by producers (e.g., farmers might apply more fertilizer in wetter years and when they expect higher prices).

Wheat is the dominant dryland crop in the region, and the Colorado Drought Mitigation Plan identifies wheat yields as a key indicator of drought impacts and vulnerability. Wheat yields for averaged for Colorado and Climate Division 1 (SE Colorado, with an extensive dryland wheat production) are shown in Figure 2.

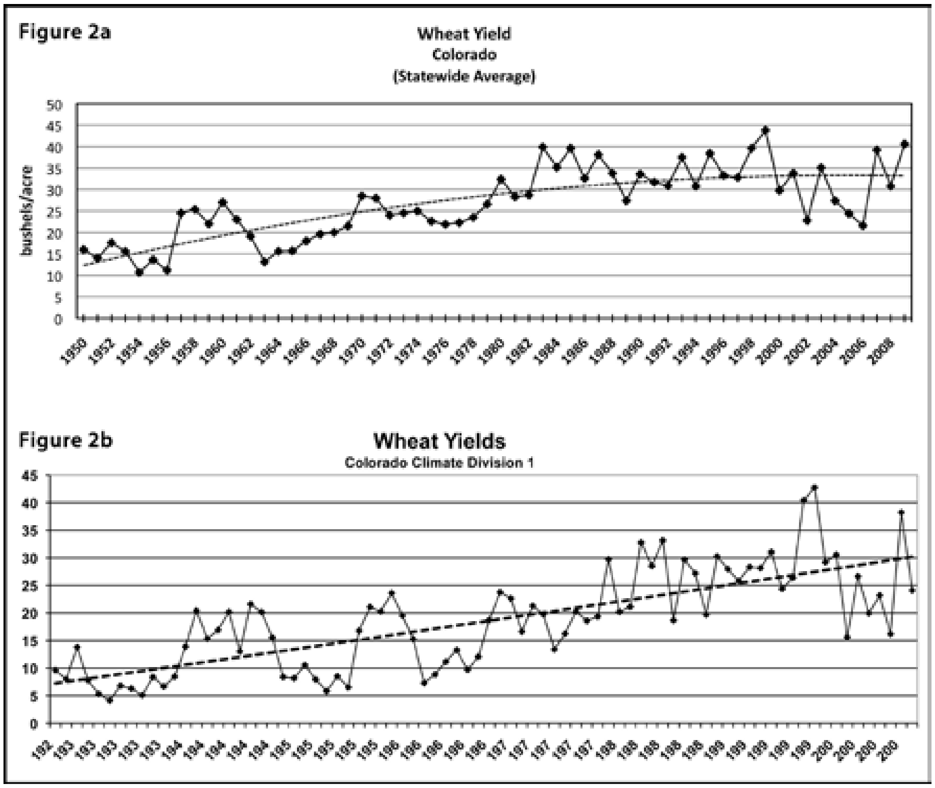

Figure 2. (a) Wheat yields (bushels/acre) for Colorado statewide, 1929-2008 (b) Wheat yields (bushels/acre) for Colorado Climate Division 1, 1929-2008.

An analysis by the CCC (CWCB, 2010, Appendix E) also indicates that fall PDSI values correlate reasonably well with wheat yields. We found similar correlations for months late in the winter wheat growing season (June and July); presumably by the end of June the PDSI has accumulated any drought deficit that would affect yields since harvest is usually in July. The correlations are not very strong (Figure 3a), but note that they are much stronger than for an irrigated crop in the same division (Figure 3b).

We compared dryland wheat yields to cumulative PDSI for large drought episodes in climate division 1 (Table 2), assuming that the broad spread of years and cumulative drought would smooth out some variations. We did this for the most significant drought episodes defined by the PDSI "run-sum", that is, the sum of the

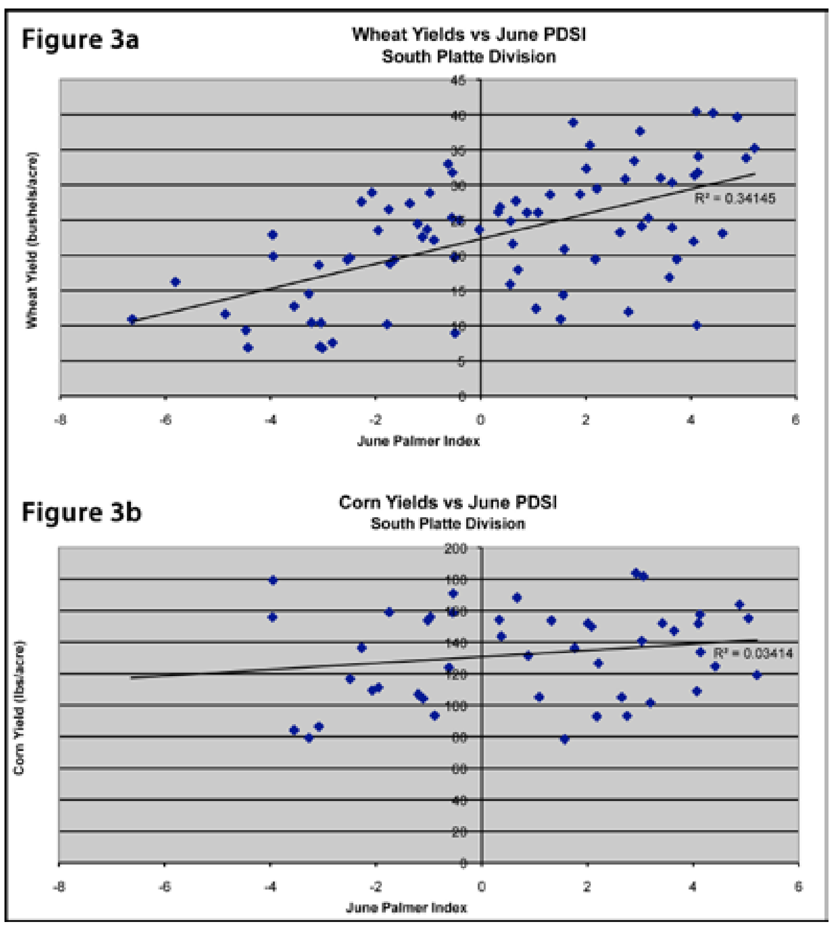

Figure 3. PDSI vs. dryland wheat yields (a) and irrigated corn yields (b), Colorado Climate Division 1 (South Platte).

monthly PDSI values in that drought period. We then calculated an average dryland wheat yield and expected yield based on polynomial curve fit to the historic yield record for that division and calculated a yield depression for each drought episode (Table 2 illustrates this analysis for Climatic Division 1).

Finally, it may be informative to track yield variability rather than, say, raw yields or total acreage. We calculated the coefficient of variation (the standard deviation divided by the mean) for dryland wheat yields for Colorado, Wyoming and Utah (Figure 4).

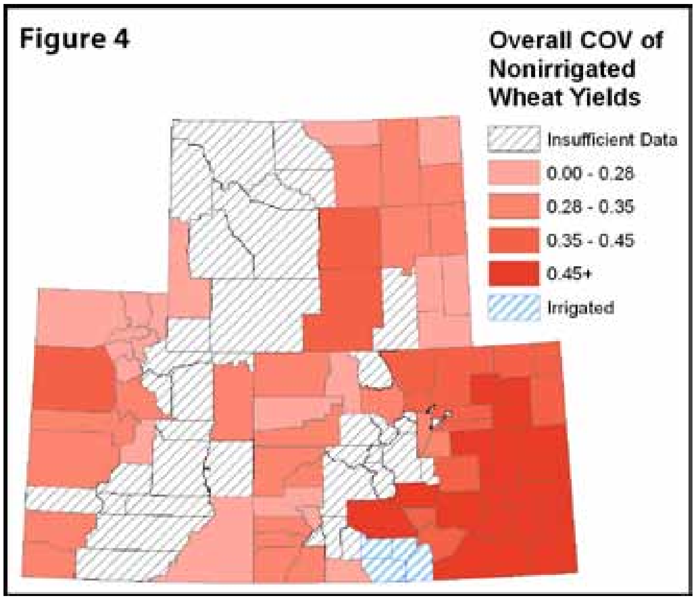

Figure 4. Coefficient of Variation of annual dryland wheat yields.

Acreage Abandoned

Harvested acreage yield reveals only part of dryland agricultural vulnerability because abandoned wheat land is both an impact but also inflates yields, so we utilized abandoned acreage (Figure 5) as another measure of drought impact, recognizing that it is sensitive to drought, quality of land, and perhaps whether farmers have insurance on that crop.

This measure shows good promise as an agricultural impact index: it is consistent over time, reflects a drought response that is well documented in the literature, and may, over time, reflect changes in vulnerability.

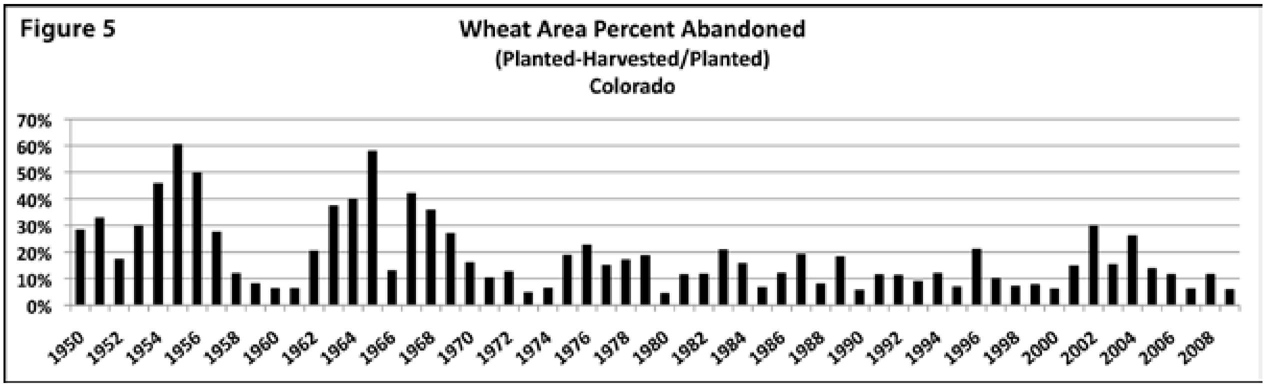

Figure 5. Wheat acreage planted but not harvested (abandoned).

Livestock Inventory

The Colorado Drought Mitigation Plan identifies livestock reductions as both an impact of, and an adaptation to, drought: ranchers and farmers might reduce herds due to poor grazing, costs of feed, or other effects. The "cattle inventory" should thus reflect this, except that state-level data might be somewhat insensitive to drought since livestock sales from an operator to, say, a feedlot, might not result in an inventory reduction though the operator has indeed taken an action and incurred costs. Additionally, herd liquidation might lag drought conditions, and might increase farm income (and thus appear as a "positive" drought effect) even though it would be considered a negative impact by most producers. Colorado state total shows the lag effects of the 2002 drought (Figure 6).

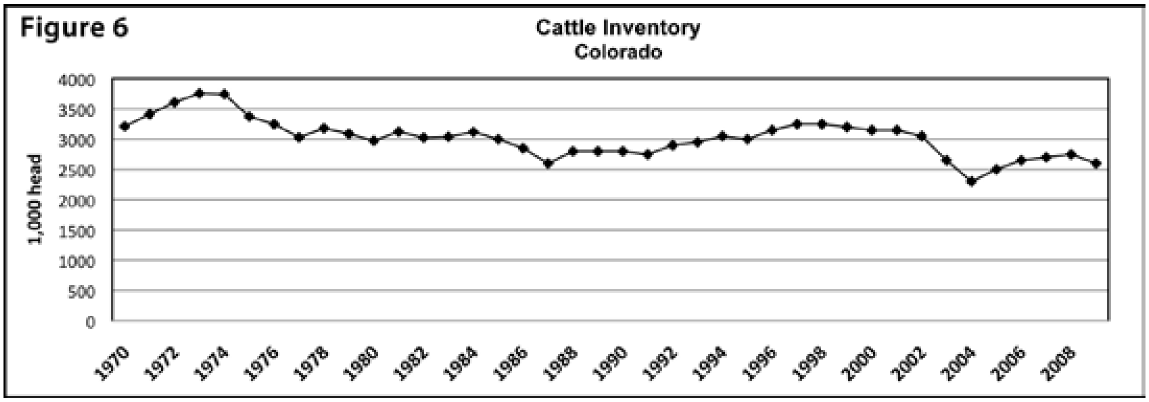

Figure 6. Colorado cattle inventory.

Land in Farms and Farm/Ranch Units

Despite fears (expressed in the media, for example) that drought will drive some operators out of business, the number of farm and ranch operations in Colorado (Figure 7a), and the total land in agriculture (Figure 7b), have been quite stable for the last few decades. This indicator would not appear to be sensitive, and it did not respond to the 2002 drought.

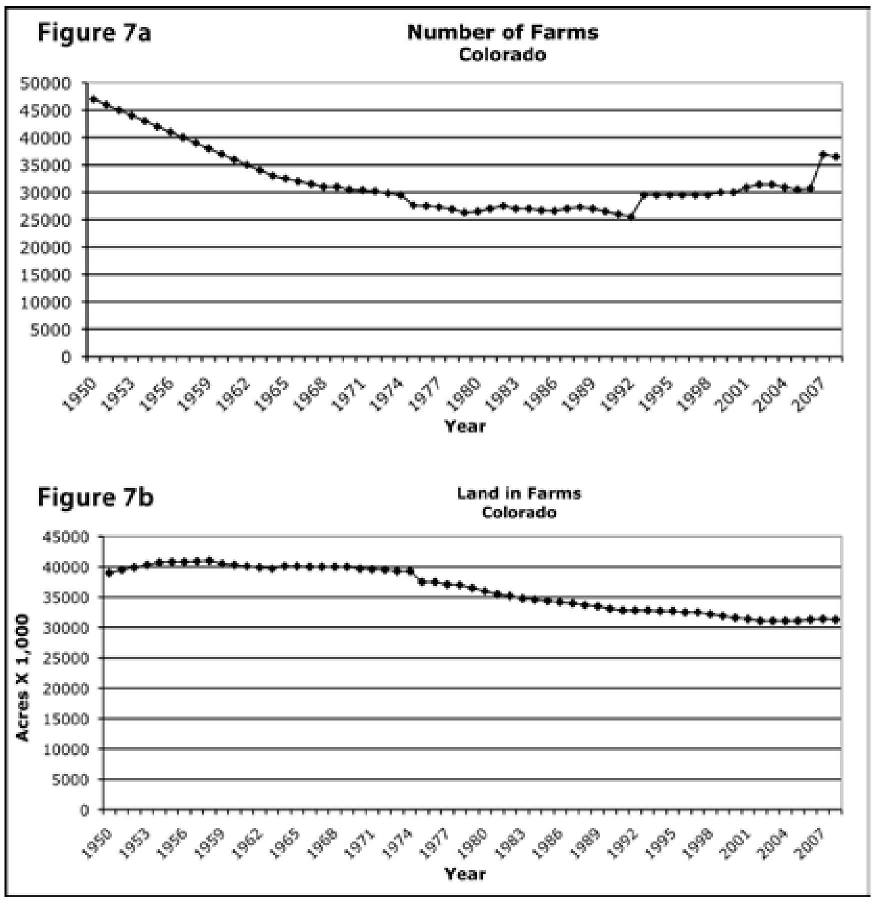

Figure 7. Number of farms and ranches (a) land in farms and ranches (b).

Crop Insurance

In the 1930s, in an attempt to help farmers reeling from the Great Depression and the Dust Bowl, Congress authorized the creation of a Federal crop insurance program. The program began as an experiment, and continued as one until Congress passed the Federal Crop Insurance Act of 1980. Still farmer participation in the program did not reach desired levels until the Federal Crop Insurance Reform Act was enacted in 1994. This act made crop-insurance program participation mandatory for farmers to be eligible for certain programs, support, loans, and benefits. Though the mandatory participation requirement was removed in 1996, participation in the crop insurance program has significantly increased since the passage of the 1994 Act. "According to estimates by the USDA National Agricultural Statistics Service, in 1998, about two-thirds of the country's total planted acreage of field crops (except for hay) was insured under the program" (http://www.rma.usda.gov/aboutrma/what/history.html).

Research on crop insurance to date has focused on the effects of climate variability on crop insurance industry participation and performance, the use of climatological data in weather insurance, factors affecting purchasing decisions, demand, and premium rates, the relationship between crop insurance and Federal disaster assistance, and the role of the government in providing risk protection (add citations). A few researchers in the Midwest have had good success at collecting and analyzing crop insurance data, especially for hail, to track and map impacts over time (e.g., Changnon et al., 2000); however, we have found no such study using crop insurance data to analyze drought impacts and vulnerability specifically.

In theory crop insurance data should provide the sort of continuous and comparable data on drought losses like that used to track trends in other hazards like floods and hurricanes. Drought is one of the hazards covered by typical crop insurance policies, the data are annual, and most crop insurance is federally subsidized and thus at least cumulative data should be public. Not only does insurance demand some estimate of loss, but the premium-to-loss ratio would tell us something about the investments in adaptation.

Thus far we have had only limited success accessing crop insurance data through public channels (though subsidized, the policies are sold through private vendors and other researchers have had to make agreements with providers to use the data). As laid out in the 2008 Farm Bill, crop insurance policies today are "sold and serviced by private insurance companies under premium rates and contract terms set by the Federal Crop Insurance Corporation (FCIC) and administered by USDA's Risk Management Agency (RMA). Premiums and delivery costs are federally subsidized" (2008 Farm Bill Side-By-Side, http://www.ers.usda.gov/farmbill/2008). The Risk Management Agency maintains state crop-insurance profiles on its website. These profiles include data on insurable crops, insured acres, total acres, and the percent acres insured. The agency also publishes a fifteen-year statewide crop insurance summary showing the number of policies earning premium, net insured acres, liability, gross premium, losses, and the loss ratio by year.

More detailed county-level data is available for download on the RMA website. The "Cause of Loss Information - Summary of Business" datasets (http://www.rma.usda.gov/data/sob.html) provide county-level information on type of crop, type of insurance, cause of loss (important when trying out to tease out drought impacts), policies earning premium, policies indemnified, net planted acres, liability, total premium, subsidy, indemnity amount, and loss ratios. Unfortunately, this data only goes back to 1989.

The most useful general measure is the loss ratio, or the ratio of payouts to total premiums. Table 3 lists the loss ratios from 1994-2008 for the state of Colorado for all causes. Figure 8 shows insurance losses for all hazards, 1995-2009, with the clear signal of the 2002 drought dominating the record and, obviously, all other hazards (flood, freeze, pathogens, etc.).

The RMA also maintains "Cause of Loss Information - Indemnities Only" datasets, which go back to 1948. However, this data does not include premium amounts, only payouts (indemnities),

Colorado
Fifteen Year Crop Insurance History

Year	Policies Earning Premium	Net Acres Insured	Liability	Gross Premium	Losses	Loss Ratio
1994	6,341	1,365,085	147,698,716	12,672,975	9,009,123	0.71
1995	22,589	3,720,646	283,010,521	22,854,646	18,911,458	0.83
1996	19,765	3,777,620	331,649,589	27,747,637	39,043,558	1.41
1997	16,848	3,606,854	345,000,486	31,818,969	18,827,774	0.59
1998	15,938	3,410,156	356,979,264	31,712,445	15,611,903	0.49
1999	16,506	3,510,795	382,844,931	36,408,936	22,878,547	0.63
2000	16,020	3,454,260	408,837,093	36,079,007	45,037,985	1.25
2001	16,064	3,580,621	456,511,070	48,707,203	51,252,573	1.05
2002	16,114	3,694,123	485,707,337	53,545,709	152,301,751	2.84
2003	17,300	4,086,388	575,112,046	75,814,048	110,028,886	1.45
2004	17,354	3,937,427	605,571,521	87,123,499	136,325,443	1.56
2005	17,168	3,929,057	579,084,551	85,126,606	98,609,196	1.16
2006	16,094	3,671,557	576,857,540	91,633,724	138,608,982	1.51
2007	16,548	6,076,509	822,136,812	138,006,852	47,249,532	0.34
2008	16,292	5,601,709	1,088,261,362	186,302,916	146,660,828	0.79
Total	**246,940**	**57,422,459**	**7,444,947,942**	**965,533,718**	**1,045,250,103**	1.08

Table 3. Colorado crop insurance history (Source: USDA Risk Management Agency).

so loss ratios cannot be calculated. And looking at drought losses in isolation misses the effects of changes in crop-insurance offerings, program regulations, and participation levels.

As it stands, crop insurance still seems to have potential for our purposes, particularly if data on total premiums prior to 1989 can be found. Further work could focus on data available from private vendors.

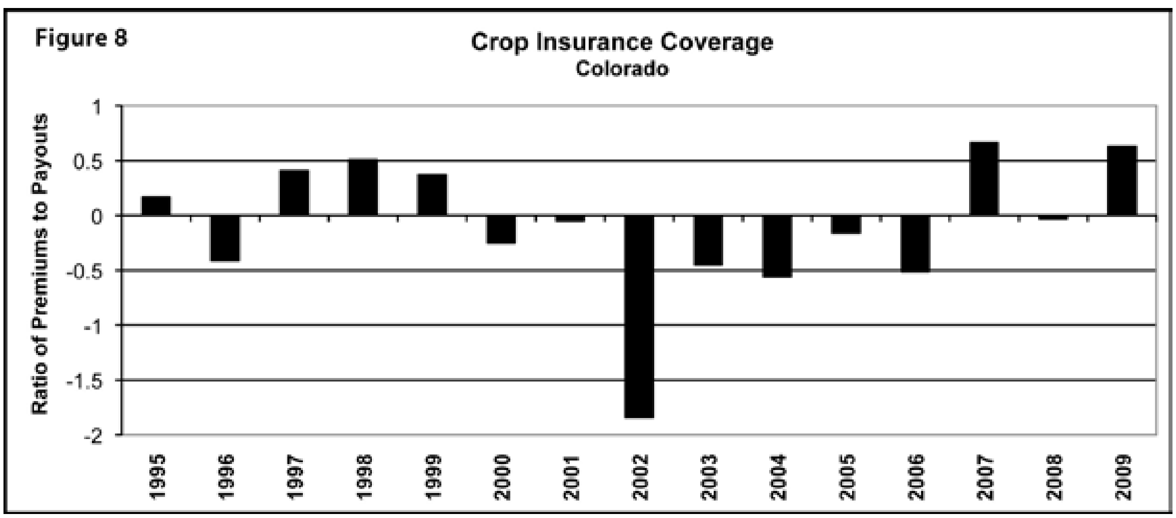

Figure 8. Colorado drought loss ratio (pay-out to premiums).

USDA and State Agricultural Disaster Declarations

According to the USDA's Farm Service Agency, "one-half to two-thirds of the counties in the United States have been designated as disaster areas in each of the past several years" (http://www.fsa.usda.gov/FSA/printapp?fileName=pf_20070209_distr_en_emergdisp.html&newsType=prfactsheet). Disaster designations come in four types: 1) Presidential major disaster declarations; 2) USDA Secretarial disaster designations; 3) Farm Service Agency (FSA) Administrator's Physical Loss Notifications and, 4) Quarantine designations. And Secretarial disaster designations are both the most widely used and the most complicated of the four. USDA Secretarial disaster designations must be requested by a governor or the governor's authorized representative, or by an Indian Tribal Council leader, and approved by the Secretary of Agriculture. The formal nature of this action, in addition to these declarations' county-level application and frequent occurrence, in theory speak to their strong potential as an indicator.

However, although information on current Secretarial disaster declarations is presented online at disasterhelp.gov, a comprehensive historical record of these declarations is difficult to come by. One spreadsheet on the main FSA website shows secretarial declarations for all counties between 2005 and 2007 (Table to come), with the cause of the declaration included. Upon contact, the national FSA office said they did not maintain electronic records of declarations beyond this.

Staff in the Colorado state Farm Service Agency office shed further light on this lack of record keeping, explaining that the national FSA office is only required to keep records on declarations for eight months. States, on the other hand, are required to do so for five years. Currently, this staff member keeps records of all Secretarial declarations made for Colorado counties from 1994 to present. Her records include the county affected, the EM Designation number, the type of disaster, the state, the incident period, the start and end dates of the designation, and the security value. Since they are not required to keep them, other states may or may not have similar records.

So though a short historical record does exist for Colorado, these disaster declarations are not as useful for determining changing drought vulnerabilities as initially hoped. Their broad use (and application to both primary and contiguous counties), subjective/political nature, inclusion of multiple simultaneous causes, and lack of a sufficiently deep historical record make Secretarial declarations a mostly ineffective vulnerability indicator.

Wildland Fires

"Where drought does strike, the risk of wildland fire soars" (http://ncar.ucar.edu/learn-more-about/climate), so it would follow that wildland fire statistics - number of fires, acres, or firefighting costs - could potential be useful as a measure of drought impacts. The National Interagency Fire Center (NIFC) coordinates wildland firefighting resources in the United States. Their website houses national wildland fire statistics, including summaries of historically significant wildland fires, prescribed fires, and national wildland fire numbers and acres from 1960-2009. Unfortunately, at the state level, data on wildland fires numbers and acres only exists from 2002 on. Figures 9 and 10 show number of fires and acres burned in Colorado from 2002-2009. Marco Perrea at Rocky Mountain Area Predictive Services branch of the NIFC informed us that fire statistics as a whole are less reliable before 2000 - and improved only on the Federal side after that. States are not required to submit fire numbers and acres to Federal reporting systems at this time. Thus, due to data limitations, wildland fire statistics are not a reliable historical indicator, but federal fire statistics after 2000 may be a worthwhile indicator into the future and the current data for Colorado do reflect the 2002 drought quite strongly.

Urban Water Restrictions

Water use restrictions in centralized systems (typically municipal water supply systems, but also private and tax district systems) are a common part of drought impact and

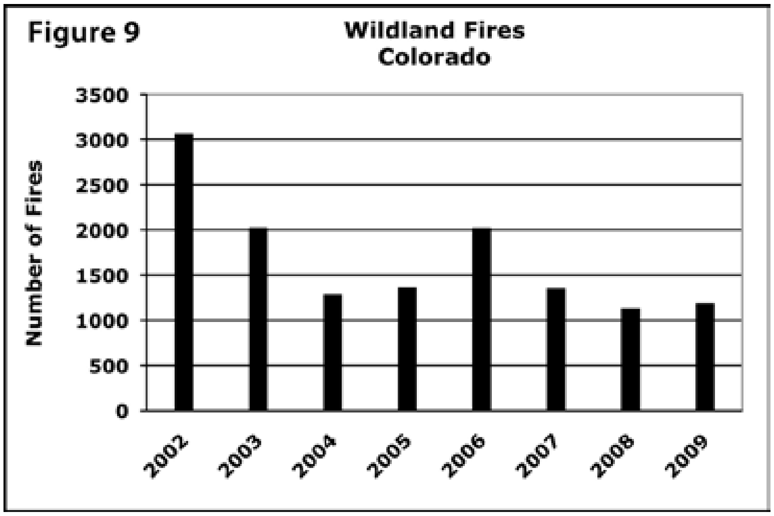

Figure 9. Number of wildland fires.

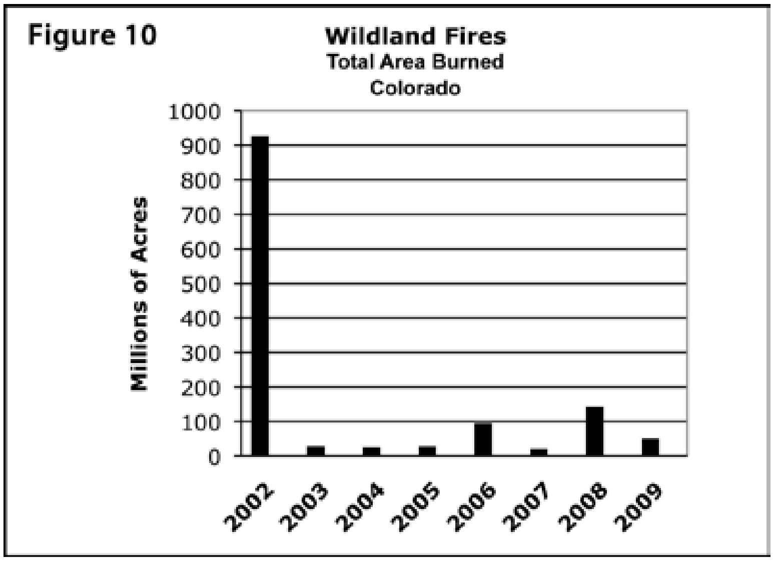

Figure 10. Acreage burned from wildland fires.

response. Restrictions would seem *prima facie* evidence of vulnerability, and the rate of formally-declared use restrictions would speak directly to drought vulnerability. Restrictions should be public record, and should be ascertainable in historical perspective as well as real-time.

We piloted the notion of an urban water restrictions index for the three state region by calling town officials in selected, mid-sized systems to develop an inventory of recent (back to 1976-77) restrictions, and to test the notion that a phone survey in mid-summer could ascertain, perhaps from a hundred systems, the simple bi-variate case of whether use restrictions had been imposed or not. We also kept an eye open for the nature of restrictions (level, targets - like car washing, lawn watering, etc.).

As shown in Table 4, of the 23 municipalities contacted, nine reported that they had never instituted mandatory watering restrictions of any kind. For a number of the communities, particularly along the Colorado Front Range, the 2002 drought was the first (and often only) time they had done so. As a result of the 2002 drought, some cities either revamped existing drought plans or created them for the first time (Aurora, CO; Longmont, CO). Two communities - Greeley, CO and St. George, UT - implement mandatory restrictions annually during summer. Through this pilot effort we also realized that in the Rocky Mountain West, mandatory watering restrictions are not always implemented as a result of drought conditions; city officials cited pump and general infrastructure malfunction and capacity limitations as reasons for mandatory restrictions in multiple places (Loveland, CO; Cedar City, UT; Cody, WY; Gillette, WY).

Our pilot study, though limited in scope, indicates that mandatory watering restrictions have not been regularly used as a coping mechanism in CO, UT, and WY up to this point. However, in order to explore changing drought impacts and vulnerability going forward, it may be helpful to create a database of mandatory restrictions for a larger number of communities across the three states. The historical record could be added, and each summer the database could be updated by calling communities and asking if they had implemented any restrictions that year. In this way a time series could be developed for future analysis.

	City	# of Restrictions	Comments
COLORADO	Loveland	2	70s: Big-Thompson flood, lost infrastructure. 2003: Drought and limited water supply. No storage.
	Lafayette	1	2002: May-December
	Longmont	1	August 5, 2002-April 21, 2003. Phase 2 of drought plan. Plan for 1 in 100 yr. drought. Created drought plan on the fly.
	Lamar	1	2004
	Durango	0	
	Grand Junction	0	
	Aurora	12	1980-1982. Since 2002 have used a water-availability stage system, with stages ranching from (1) Up to 3 days of your choice to (5) No outdoor use.
	Greeley	Annually	Every year from approximately April 15-end of watering season; assigned odd/even schedule.
	Pueblo	1	Summer 2002
UTAH	Cedar City	2	Mechanical failure caused wells to go down.
	Moab	0	None in past 10 yrs. In 60’s was common, before city had enough water.
	Springville	1	Early 2000’s: Odd/even schedule. Usage actually went up.
	Provo	1	1977
	Ogden	0	
	Sandy	0	
	St. George	Annually	Usually institute daytime watering restrictions during summer; temperatures over 100 degrees, keeps residents mindful of wise water use even when not in drought.
WYOMING	Rock Springs	2	None since 1995. Some in late 80’s, early 90’s, but drought hasn’t been a problem recently.
	Rawlins	0	
	Casper	1	Last was in 2006: February-April. Just got out of a 9-year drought. Didn’t have any historical information.
	Gillette	0	Building new pipeline to increase capacity.
	Cody	1	Had alternate-day schedule for 6-7 yrs. Due to pump capacity, not drought shortage.
	Sheridan	2	Early 2000’s
	Laramie	0	
	Green River	0	

Next Steps

Some potential indicators deserve more work, especially insurance data and urban water supply restrictions. More effort is also needed in other sectors, especially recreation and tourism, as well as the overall state or regional economy.

References

Bowden, M.J., R.W. Kates, P.A. Kay, W.E. Riebsame, R. Warrick, D.L. Johnson, H.A. Gould, and D. Weiner (1981) The effect of climate fluctuations on human populations: Two hypotheses. In Climate and history: Studies in past climates and their impact on Man, ed. T.M. Wigley, M.J. Ingram, and G. Farmer, 479-513. Cambridge, U.K.: Cambridge University Press.

CCSP (2008) Weather and climate extremes in a changing climate. Regions of focus: North America, Hawaii, Caribbean, and US Pacific Islands. A report by the US Climate Change Science Program and the Subcommittee on Global Change Research. [Karl TR, Meehl GA, Miller CD et al (eds)]. Department of Commerce, NOAA's National Climatic Data Center, Washington, DC.

Changnon, S.A., R.A. Pielke, Jr., D. Changnon, R.T. Sylves, and R.Paulwarty (2000) Human factors explain the increase losses from weather and climate extremes. Bulle. Amer. Met. Soc. 81: 437-441.

Colorado Water Conservation Board (2010) Colorado Drought Mitigation and Response Plan. Plan (Draft). Plus annexes and appendices, available at: http://cwcb.state.co.us.

Doeskin, N.J., T.B. McKee, and J. Kleist (1991a) Development of a Surface Water Supply Index for the Western United States. Climatology report 91-3, Colorado Climate Center, Fort Collins, CO.

Doeskin, N.J., T.B. McKee, and D. Garen (1991b) Drought Monitoring in the Western United States Using a Surface Water Supply Index. Proceedings of the 7th Conference on Applied Climatology, Salt Lake City, UT. American Meteorological Society, Boston.

Dupigny-Giroux, L. A. (2001) Towards Characterizing and Planning for Drought in Vermont - Part II: Policy Implications. Journal of the American Water Resources Association 37(3): 527-531.

Dziegieleski, B., H.P. Garbharran, and J.F. Langowski, Jr. (1993) Lessons learned from the California Drought (1987-1992). Institute for Water Resources report 93-NDS-5. U.S. Army Corps of Engineers, Fort Belvoir, VA.

Downton, M.W., Miller, J.Z.B., and Pielke, R.A., Jr. 2005. Reanalysis of U.S. national weather service flood loss database. Natural Hazards Review 6: 13-22.

Fontaine, M. M. and A. C. Steinemann (2009) Assessing Vulnerability to Natural Hazards: Impact-Based Method and Application to Drought in Washington State. Natural Hazards Review 10: 11-18.

Gertner J (2007) The future is drying up. NY Times Mag October 21:68-77, 104, 154-155.

Henz, J., Seth Turner, S. William Badini, W. and J. Kenny (2004) Historical Perspectives on Colorado Drought. Colorado Water Conservation Board Drought and Water Supply Assessment (Chapter 1). Pp. 1-22. Available at: http://cwcb.state.co.us/Apps/Drought_Water/pdf/Chapter%201.pdf.

Hrezo, M. S., P. G. Bridgeman, et al. (1986) Managing Drought Through Triggering Mechanisms.

Journal of the American Water Works Association 78: 46-51.

Hill, Troy D. and Colin Polsky (2007) Suburbanization and drought: A mixed methods vulnerability assessment in rainy Massachusetts. Environmental Hazards 7: 291-301

Knutson, C. L. and M. J. Hayes (2001) South Carolina Drought Mitigation and Response Assessment: 1998-2000 Drought. Quick Response Research Report #136. Boulder, Colorado, Natural Hazards Research and Applications Information Center.

McKee, T.B., N.J. Doeskin, and J. Kleist, C.J. Schrier, and W.P. Stanton (2000) A History of drought in Colorado. Water in the Blaance, No. 9. Colorado Water Resources Research Institute and Colorado Climate Center, Colorado State University, Fort Collins.

Mishra, A. K. and V. P. Singh (2010) A Review of Drought Concepts. Journal of Hydrology 391: 202-216.

Parton, W.J, M.P. Gutman, and D. Ojima (2007) Long-Term trends in population, farm income, and crop production in the Great Plains. BioScience 57:737-747.

Palmer, R. N., S. L. Kutzing, et al. (2002) Developing Drought Triggers and Drought Responses: An Application in Georgia. Amer. Soc. Civil Engineer. Conference Proceedings.

Pielke, R.A., Sr., N. Doesken, O. Bliss, T. Green, C. Chaffin, J. D. Salas, C.A. Woodhouse, J.J. Lukas, K. Wolter (2005) Drought 2002 in Colorado: An unprecendented drought or a routine drought? Pure and Applied Geophysics 162: 1455-1479.

Pielke Jr., RA (2007) Future economic damage from tropical cyclones: Sensitivities to societal and climate changes. Phil Trans R Soc A 365:2717-2729

Pielke Jr., RA, Gratz J, Landsea CW et al (2008) Normalized hurricane damages in the United States: 1900-2005. Nat Hazards Rev 9:29-42.

Riebsame WE, Changnon SA, Karl TR (1991) Drought and natural resources management in the United States. Westview Press, Boulder, CO.

Russell, Clifford S., David G. Arey, and Robert W. Kates (1970) Drought and Water Supply: Implications of the Massachusetts Experience for Municipal Planning. Johns Hopkins Press: Baltimore.

Shafer, B.A. and L.E. Dezman (1982) Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. Proceedings of the Western Snow Conference, April 18-20, Fort Collins, CO, pp. 164-175.

State of Colorado (2010) Wilhite, D.A., W.E. Easterling, and D.A. Wood, eds. (1987) Planning for drought: toward a reduction of societal vulnerability. Westview Press, Boulder, CO.

Steinemann, A. C. and L. F. N. Cavalcanti (2006) Developing Multiple Indicators and Triggers for Drought Plans. Journal of Water Resources Planning and Management 132: 164-174.

Wilhite, D.A. (1991) Drought Planning and State Government: Current Status, Bulle. of the Am. Met. Soc., 72, 1531-1536.

Wilhite, D.A., ed. (1993) Drought assessment, management, and planning: theory and case studies. Kluwer, Boston.