

EARLIER NESTING BY A PREDATORY BIRD IS ASSOCIATED WITH HUMAN
ADAPTATIONS TO CLIMATE CHANGE

by

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DEDICATION

This thesis is dedicated to my wife, Cassi, who believed in me enough to move across the country and away from friends and family just to give me a chance to pursue my dream. Thank you for never giving up on me.

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ABSTRACT

Advancing growing seasons and prey abundance drive earlier breeding in dietary specialists because, ultimately, consumers benefit by timing their reproduction to coincide with peak prey abundance. The selective pressure to breed earlier may be lower for species that forage on diverse prey items that vary in abundance both spatially and temporally. The selective pressure may be reduced further if predators have access to a mosaic of habitats, each of which having different shifts in growing seasons. We studied whether earlier breeding of a predatory generalist, the American kestrel (*Falco sparverius*) nesting in a mosaic of habitat types was associated with changes in local growing seasons and prey abundance. The study area was predominately mixed sagebrush steppe/invasive grass cover types and irrigation-dependent cover types, which included crops, pastures, and lawns. Both cover types could typically be found within an American kestrel's territory. From 1992-2015, we examined the potential relationship between prey abundance (small mammals) and Normalized Difference Vegetation Index (NDVI), recorded seasonal changes in NDVI to estimate the start of the growing season (SoGS) in irrigated and non-irrigated land covers, and used annual SoGS estimates to predict the timing of kestrel nesting. Finally, we related changes in the timing of SoGS in irrigated land cover to planting of crops and weather. The positive relationship between maximum NDVI values and small mammal abundance indicated that as maximum NDVI values increased so did small mammal abundance. This suggested that NDVI was a useful proxy for estimating shifts in the timing of prey abundance over time. NDVI-

estimated SoGS advanced significantly in irrigated land cover ($\beta = -1.09 \pm 0.30$ SE) but not in non-irrigated land cover ($\beta = -0.57 \pm 0.53$). Date of kestrel nest initiation was positively associated with the SoGS in irrigated land cover and the date of nest initiation advanced 15 days in the last 24 years. Irrigated SoGS advance was associated with earlier planting of crops following warmer winters, which is a commonly reported human adaptation to climate change. Within their territories, most kestrels had access to both irrigated (shifting SoGS) and non-irrigated (no change in SoGS) land covers, suggesting that kestrels may preferentially track prey in irrigated land cover compared to prey from non-irrigated land cover. Kestrels may track irrigated SoGS because irrigated land cover provided higher quality prey, or earlier prey abundance may enable kestrel response to other selective pressures on nesting phenology, such as seasonal declines in fecundity or competition for high-quality mates. Future studies of climate change and wildlife in human-dominated environments should consider synergies between climate and human adaptations. Finally, studies of climate change effects should consider utilizing direct measures of growing seasons, such as NDVI, that may be more reliable indicators of environmental change than temperature alone.

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LIST OF ABBREVIATIONS

ENVI	Exelis Visual Information Solutions
GDDs	Growing Degree Days
NDVI	Normalized Difference Vegetation Index
SoGS	Start of the growing season
TOA	Top of Atmospheric

INTRODUCTION

Shifts in breeding phenology are a common biological response to climate change. There is evidence of earlier breeding in amphibians (Beebee 1995; Gibbs & Breisch 2001), reptiles (Telemeco, Elphick & Shine 2009), birds (Brown, Li & Bhagabati 1999; Dunn & Winkler 1999; Hussell 2003; Torti & Dunn 2005), and mammals (Reale et al. 2003; Millar & Herdman 2004) from Antarctica to North America and Europe. Earlier breeding is a common pattern affecting diverse taxa, but most hypotheses regarding climate change and breeding phenology have been generated from studies of passerine birds that specialize on insects (Crick et al. 1997; Forchhammer, Post & Stenseth 1998; Both et al. 2004). In these systems, warming spring temperatures have affected plant phenology and insect emergence. Early peaks in prey abundance increases the selective pressure to nest earlier because birds benefit by timing their reproduction to coincide with periods of high food abundance (Lack 1954) and, for some species, nesting phenology has advanced (Crick et al. 1997; Dunn & Winkler 1999; Both & Visser 2005; Pearce-Higgins, Yalden & Whittingham 2005; Bauer et al. 2010).

The ability of primary productivity and prey phenology to drive change in avian nesting phenology is most likely to occur when birds specialize on relatively few prey species that exhibit synchronous, highly peaked abundance (van Noordwijk, McCleery & Perrins 1995), or when most of a bird's different prey species experience common phenology shifts (Dunn & Winkler 1999). If and the extent to which generalists or species that forage in mixed habitat types are as affected by changes in primary

productivity and prey abundance is unclear. Generalist may be less likely to advance their breeding phenology in response to one (or a few) prey species because they often forage on a variety of prey items with asynchronous abundance patterns (Both et al. 2010) or heterogeneous distributions. These species may have the potential to switch among possible prey items or change their distribution, whereas specialist species may be forced to adjust their nesting phenology to match the timing of their prey. Further, rates of change in primary productivity and prey abundance will vary with different plant species that require different numbers of growing degree days to germinate or flower. Species that live in a mosaic of vegetation types may experience different rates of phenological changes in prey abundance.

Phenology shifts may be further confounded by changes in human activities for species that nest in human-dominated landscapes (Plummer, Siriwardena, Conway, Risely & Toms 2015). In the Northern Hemisphere, growing seasons are lengthening and late frosts are occurring significantly earlier (Schwartz, Ahas & Aasa 2006). Farmers are adapting to these changes by planting crops earlier each year and introducing new cultivars which has resulted in plants with higher biomass and increased yield (Kucharik 2006). Without these adaptations to climate change, crops such as maize may have experienced substantial losses in yield, but they have instead increased their overall yield (Liu, Hubbard, Lin & Yang 2013). Changes in planting and growing degree days (GDDs) could result in accelerated changes in nesting phenology in human systems when compared to natural systems.

Unfortunately, it can be difficult to establish coupled phenology change without long-term studies on both predators and prey. In lieu of prey data, many studies have

used remote sensing data to measure land cover characteristics that may act as a proxy for prey abundance (Pettorelli et al. 2005; Balbontin et al. 2009; Trierweiler et al. 2013; Cole et al. 2015; McKinnon, Stanley & Stutchbury 2015). Specifically, the amount of infrared and visible red light absorbed or reflected back into space can be indexed by Normalized Difference Vegetation Index (NDVI) (Reed et al. 1994; Pettorelli et al. 2011). Growing, green vegetation has higher NDVI values than sparse, less photosynthetically active plants (Pettorelli et al. 2011). Seasonal changes in NDVI can be used to estimate the start of growing season (SoGS), and track the increase in vegetation greenness that may elicit a response from primary consumers like insects and small mammals (Reed et al. 1994). For example, Trierweiler et al. (2013) used NDVI as a proxy for grasshoppers and found that wintering Montagu's harriers (*Circus pygargus*) tracked grasshoppers across West Africa spatially and temporally. Cole, Long, Zelazowski, Szulkin & Sheldon (2015) showed that NDVI predicted prey abundance for great tits (*Parus major*) and blue tits (*Cyanistes caeruleus*) and that reproductive phenology for both species could be predicted using NDVI.

American kestrels (*Falco sparverius*) are small falcons that feed on small mammals, reptiles, insects, and birds (Smallwood & Bird 2002). Kestrels are secondary cavity-nesters and use a variety of habitats that include shrub and grasslands and agricultural and suburban areas (Bird & Palmer 1988). In southwestern Idaho, for instance, American kestrels occupy nesting territories often containing both sagebrush steppe and invasive grass habitats and irrigation dependent (crops, pastures, and lawns) habitats. For American kestrels in this region, the start of nesting (nest initiation) has advanced approximately 15 days between 1992 and 2015. Earlier nesting by American

kestrels has been associated with warmer winter minimum temperatures, but there have not been concomitant changes in spring temperatures (Heath, Steenhof & Foster 2012). Our objectives were (1) to evaluate whether advancing nesting phenology American kestrels living in heterogeneous habitats with access to both irrigated and non-irrigated land covers was associated with changes in the timing of prey abundance and the onset of the growing season; and (2) assess the potential influence of weather and human activities on changes in the start of the growing season (Figure 1). To do this we: 1) evaluated whether NDVI could be used as a reliable index of seasonal prey abundance, 2) used NDVI to estimate changes in the SoGS and, presumably, seasonal prey abundance, from 1992-2015, 3) evaluated the potential relationship between the changes in NDVI over time and corresponding changes in the nest initiation dates of American kestrels, and 4) assessed the relationship between the SoGS and winter temperatures and the timing of planting of crops by local farmers

Methods

Study Area

The southwestern Idaho study area (43° N 116 ° W) included between 90-126 nest boxes available to kestrels depending on the year (Steenhof & Heath 2009). The nest boxes were placed on highway signs along Interstate 84, on trees in rural residential areas near Kuna, Idaho, and on wooden poles throughout agricultural and exurban areas south of Boise and Meridian, Idaho. Kestrels also had the opportunity within our study area to nest in old trees and buildings as well as boxes erected by others. A 900m radius around each nest box was considered a “nesting territory” because it represented a confined

location where kestrels nested and no more than one pair bred there at a time (Newton & Marquiss 1982; Steenhof & Heath 2013).

The study area was 65 km x 22 km and encompassed approximately 1000-km² of open agricultural and sagebrush steppe land cover. The agricultural areas (referred to as irrigated land cover) primarily consisted of irrigated cropland where potatoes, barley, spring wheat, winter wheat, alfalfa, and sugar beets were often planted. The sagebrush steppe (referred to as non-irrigated land cover) was primarily a mixture of sagebrush and invasive grasses. Most kestrel territories in our study area contained both irrigated and non-irrigated land covers. The 53 kestrel territories sampled within our study area contained an average of 59.42 ± 32.44 % irrigated and 39.8 ± 32.44 % non-irrigated systems ($\bar{x} \pm SE$, Strasser 2010).

Normalized Difference Vegetation Index (NDVI)

NDVI values were estimated using Landsat 5 and 8 images (data provided courtesy of the U.S. Geological Survey) of the study area (path 42, row 30) taken every 16 days from 1992-2015 (except for January 2012-mid April 2013 when the Landsat 5 satellite was down until Landsat 8 satellite started). All image files were calibrated in ENVI version 5.2 (Exelis Visual Information Solutions, Boulder, Colorado) by calculating the radiance values and then calculating the top of atmospheric (TOA) reflectance values (Appendix A). Landsat 5 images were calibrated and TOA reflectance was determined using calculations described by Chander & Markham (2003) and revisited by Chander, Markham & Helder (2009). Landsat 8 images were calibrated and TOA reflectance was determined using the calculations described in the Landsat 8 (L8)

Data Users Handbook (2016). NDVI was calculated using the calibrated images and Equation 1 for Landsat 5 and Equation 2 for Landsat 8 (Appendix A).

$$\text{Landsat 5 NDVI: } (Band\ 4 - Band\ 3) / (Band\ 4 + Band\ 3) \quad (\text{eqn. 1})$$

$$\text{Landsat 8 NDVI: } (Band\ 5 - Band\ 4) / (Band\ 5 + Band\ 4) \quad (\text{eqn. 2})$$

We selected 34 non-irrigated and 37 irrigated, 80 x 70 m sites within our study area using ArcGIS 10.1 (Esri 2012, Redlands, CA). These sites included 28 sites where we also conducted prey surveys (see below). All sites were selected in a stratified random fashion from kestrel territories where no land use change had occurred between 1992 and 2015 and were all in close proximity to a kestrel nest box. Although the majority of kestrel territories contained both irrigated and non-irrigated habitat, we classified a site based on the 80 x 70 m site closest to the kestrel nest box. The NDVI layers created in ENVI were loaded into ArcGIS 10.1 and maximum NDVI values were extracted for each individual site. We selected maximum NDVI values because minimum values can be contaminated by cloud cover and ground conditions (Pettorelli et al. 2005; Bradley, Jacob, Hermance & Mustard 2007). All images were visually inspected for cloud cover and any images with greater than 25% cloud cover obscuring our overall study area were excluded from the analysis. For all images with less than 25% cloud cover obscuring the overall study area, individual 80 x 70 m sites were inspected and removed from analyses if obscured by clouds. Once maximum NDVI values for each site were extracted, all values were sorted and combined into two groups based on habitat type (irrigated or non-irrigated) within the 80 x 70 m site. Because of differences in vegetation (Bradley et al. 2007), we created separate estimates for prey (see below) and NDVI in irrigated and non-irrigated land covers. Seasonal trends in NDVI for the exact 80 x 70 m grid where prey

surveys were conducted (see below) were compared for the seasonal trends in prey abundance for each of the 28 sites to determine if NDVI could be used as a proxy for prey abundance.

To account for any missing values due to cloud contamination or unavailable data, a combination of approaches was used. When missing two data points or less, linear interpolation was used to fill the missing data. A third order harmonic regression analysis that was trained by the year before and the year after was used to generate an average annual NDVI curve. If the values were less than the next known NDVI value, the annual curve values were used to replace missing data gaps (Brooks, Thomas, Wynne & Coulston 2012). At times the third order harmonic regression was influenced by large data gaps and would estimate erroneously high NDVI values. Annual curve values were not used if they were greater than adjacent known NDVI values because erroneous maximums could influence the start of the growing season (see below). This resulted in a few remaining data gaps that were replaced by weekly averages of known NDVI values. Annual NDVI curves and 3-day moving averages were plotted and the date at which the moving average intercepted the annual NDVI curve was considered the SoGS because it signifies the date NDVI makes a sudden increase and could be explained by photosynthetic activity (Reed et al. 1994).

Prey Surveys

The mix of irrigated and non-irrigated cover types around their nest boxes provides kestrels with multiple food providing systems from which to choose. Based on camera surveillance data at nest boxes, the main prey items of American kestrels in our study area were small mammals (Appendix B). Seasonal abundance of small mammals

was assessed using presence/absence data collected from track plates enclosed in tubes modified from the design of Drennan, Beir & Dodd (1998), Glennon, Porter & Demers (2002), and Wiewel, Clark & Sovada (2007). The tubes were 30 cm long on top and 20 cm long on the bottom and were constructed of two halves of plastic rain gutter taped together on one side and held shut by one rubber band. This design allowed the track plates to be rainproof, light weight, and easy to deploy (Drennan et al. 1998; Glennon et al. 2002; Wiewel et al. 2007). The track plates were 18 cm long aluminum flashing placed on the bottom of the tube and held in place by Velcro. Each end of the track plate was covered by a felt pad that was coated in ink, a 1:1 mixture of lamp black (DanielSmith, Inc., Seattle, WA, USA) and paraffin oil (STE Oil Company, Inc., San Marcos, TX, USA). A piece of white paper between each felt pad recorded footprints. Traps were baited with a small amount of peanut butter along the top half of the track plate tube. Traps were secured in place by two tent stakes.

Small mammals were sampled near 28 kestrel nest boxes in 2014. At each nest box, 20 track plates were placed in a 5 x 4 rectangular trapping grid with 20 m between each track plate and all within 100 m of the nest box. Cover types were classified based on the vegetation present where small mammals were sampled regardless of cover type in the territory surrounding the nest box. Ten track plate plots were in irrigated land cover and 18 were in non-irrigated land cover. Track plates were deployed at each nest box site for three consecutive days each month from March through July. Trapping order was selected in a stratified random order so that the sites sampled last during a previous month were not the first sampled the next month, and sites were not trapped in the same order each month. Track plates were checked once per day during which time tracks were

recorded as present or absent. If tracks were present the paper was replaced, the location of trap was recorded, and bait was reapplied.

Animal tracks were identified using Murie & Elbroch (2005) and, at some trap sites, motion-activated trail cameras (Bushnell ® HD Trophy Cameras, Overland Park, KS, USA). We used trail cameras placed near several track plates within different kestrel territories to obtain visual confirmation of the identity of small mammals visiting traps. Ultimately tracks were classified as being from: mountain cottontail (*Sylvilagus nuttallii*), ground squirrel (*Urocitellus* sp.), or small mammal, the latter of which generally were deer mice (*Peromyscus maniculatus*) and voles (*Microtis* sp.). Voles and deer mice were grouped together because their footprints were of similar size and both were potential kestrel prey (Appendix B).

Nesting Phenology

From 1992 to 2015, except for 2007, American kestrels nesting in boxes in southwestern Idaho were monitored (Steenhof & Heath 2009; Steenhof & Peterson 2009). Prior to the nesting season each year, nest boxes were cleaned and lined with pine shavings. Beginning in early March, boxes were visited every 7-21 days to determine kestrel occupancy and clutch size in actual nests. The mean nest discovery dates (average date when eggs were first discovered in a nest, regardless of number of eggs) each year were used as an index of annual timing of kestrel nesting because clutch initiation dates (date first egg was laid) were not available for the years 1992 to 2006 (Steenhof & Heath 2009). These dates correlated well with hatching dates, as nests discovered early hatched early (Pearson correlations analysis: $r = 0.89$, $n = 577$, $P < 0.001$), so we considered them to be a reliable index of clutch initiation date. Nest discovery dates for the years 1992 to

2015 ranged from 14 March to 12 July and averaged 26 April. Mean nest discovery date was used, instead of the median nest discovery date, because monitoring the mean nesting event allows for monitoring of population level effects (Reed, Jenouvrier & Visser 2013). All methods and protocols described above were approved by the Boise State University IACUC review board (IACUC Approval Numbers 006-AC14-005, 006-01-006, and 006-05-004) and conducted under scientific permits issued to J. Heath from state and federal authorities.

Crop Phenology and Weather

We obtained Idaho Crop Progress and Condition reports from the USDA National Agricultural Statistics Service for years 1992 to 2013 to examine whether some of Idaho's most commonly planted crops were planted earlier in the year over time. The USDA stopped reporting district-specific data and transitioned to statewide data in 2014 so years 2014 and 2015 were excluded from our analysis. We examined planting patterns over time for the following crops: barley, potatoes, spring wheat, and sugar beets.

We used daily winter minimum temperature anomaly data from the Global Historical Climatology Network gridded dataset (HadGHCND, National Climatic Data Center 2009) station nearest the study area (station 1295) to examine the potential effect of winter temperature change on crop planting dates from 1992-2013 (see Heath et al. 2012). Winter months were November to February to coincide with the months when overwintering kestrels were present (Crick & Sparks 1999; Both et al. 2010; Heath et al. 2012). Daily anomalies were the difference of each daily minimum temperature from a daily 'base value' (Caesar, Alexander & Vose 2006). Daily 'base' minimum temperatures

were calculated from the climate station's minimum temperature records for 1961-1990 using a five-day window centered on each day (Caesar et al. 2006).

Statistical Analyses

Prey Abundance

An index of small mammal abundance was estimated for each American kestrel territory from the presence and absence data collected using track traps following methods in Royle & Nichols (2003) in package 'unmarked' (Fiske & Chandler 2011). Indices were derived using territory and month as covariates. The daily indexes for each three day sampling period were averaged for each territory and represented the monthly prey abundance at the territory level. The use of NDVI as a proxy for prey abundance was validated using a liner mixed-effect model that assessed the potential effects of NDVI, cover type, and the interaction between NDVI and cover type on small mammal abundance index values and included site as the random effect.

NDVI and Nesting Phenology

We examined the potential relationship between mean nest discovery date and SoGS for irrigated and non-irrigated land covers using a linear model. We did not separate nest discovery dates based on land cover type as with small mammal and NDVI analyses because kestrels had access to both land covers surrounding their nest box. We examined seasonal changes in maximum NDVI values for 2014 separately for irrigated and non-irrigated land covers using linear models with Julian date and Julian date-squared as predictors. We assessed potential trends in the annual SoGS for irrigated and non-irrigated land covers separately using linear models. Annual trends in kestrel nesting

phenology were examined using linear models with average nest discovery date as the dependent variable and year as the independent variable.

Crop Phenology and Weather

We used linear models to determine if the percent of land planted with each crop planted was higher earlier in the year from 1992 to 2013. All crop types were combined within a single linear model and we used crop type, initial reporting date, and year to examine whether the proportion of land planted at initial reporting had changed over time. The predictor variable winter temperature anomaly, instead of year, was used to examine whether the proportion of land planted with a crop depended on the preceding winter weather. Finally, we examined whether the proportion of land planted predicted SoGS from 1992 to 2013. All analyses were performed in R v. 3.1.1. Results are presented as $\beta \pm SE$ throughout.

Results

Prey Abundance

We deployed a total of 8,280 track plates from March to July and recorded 4,949 (59.8%) track plates positive with small mammal foot prints, 3,755 (75.9%) of which were deer mouse or vole. Monthly abundance index values for non-irrigated trapping plots within kestrel territory ($n = 18$) locations ranged from 0.02 – 2.04 mammals/trap (local abundance) and showed a seasonal peak in mid-May. Local abundance values in irrigated land cover ranged from 0.02 - 1.84 mammals/trap and peaked in early July (Figure 2). For non-irrigated and irrigated land covers, maximum NDVI values peaked on 10 May 2014 and 9 July 2014, respectively (Figure 3). Thus, temporal changes in abundance of small mammals followed a similar pattern as NDVI. There was a

significant positive relationship between small mammal abundance and maximum NDVI values in both land covers (Linear mixed-effect model: $\beta = 4.81 \pm 2.3$, $P < 0.001$, $R^2 = 0.34$, Figure 4). Therefore, we considered maximum NDVI values to be a predictor of seasonal small mammal abundance in both non-irrigated and irrigated land covers.

NDVI

Between 1992 and 2015, SoGS for irrigated and non-irrigated land covers ranged from 12 March to 29 April and from 4 February to 7 April, respectively (Figure 5). SoGS significantly advanced by 26 ± 14 days ($\bar{x} \pm SE$) from 1992-2015 in irrigated land cover (Linear regression: $\beta = -1.09 \pm 0.3$, $F_{1, 21} = 13.35$, $P < 0.002$), but not for non-irrigated land cover ($\beta = -0.57 \pm 0.53$, $F_{1, 21} = 1.14$, $P = 0.30$).

Nesting Phenology

From 1992-2015, excluding 2007, there were 1069 kestrel nest discoveries ranging in date from 14 March to 9 July. The mean nest discovery dates ranged from 18 April to 11 May and showed a significant advancement of 15 days over 24 years (Linear regression: $\beta = -0.61 \pm 0.12$, $F_{1, 21} = 26.64$, $P < 0.001$, Figure 6). Kestrel nest discovery dates were related to SoGS in irrigated land cover ($\beta = 0.32 \pm 0.08$, $F_{1, 20} = 16.08$, $P < 0.001$, Figure 7), but not the SoGS in non-irrigated land cover ($\beta = 0.07 \pm 0.07$, $F_{1, 20} = 1.03$, $P < 0.32$, Figure 8).

Crop Phenology and Weather

From 1992-2013, the percent of each crop planted was higher on the first day of reporting when controlling for crop type and day of report, which likely reflects earlier planting (Linear regression: $\beta = 0.87 \pm 0.39$, $F_{1, 80} = 5.03$, $P < 0.03$, Figure 9). Warmer winter temperature anomalies resulted in a higher percentage of crops being planted on

the first day of reporting the following spring ($\beta = 6.59 \pm 2.41$, $F_{1,72} = 7.50$, $P = 0.008$, Figures 10). As farmers planted their crops earlier in the year, the NDVI estimated SoGS significantly advanced ($\beta = -0.75 \pm 0.21$, $F_{1,72} = 12.51$, $P < 0.001$, Figure 11). This suggests that farmers are having an impact on the SoGS in irrigated land cover by advancing the emergence of vegetation, and is consistent with NDVI-based SoGS for irrigated land cover (Figure 1).

Discussion

We found that NDVI was a reliable indicator of seasonal prey abundance and that annual NDVI patterns from 1992-2015 indicated that the SoGS has advanced in irrigated, but not non-irrigated land cover within our study area in southwestern Idaho. American kestrel nest initiation was positively associated with the SoGS in irrigated land cover. The SoGS has advanced in irrigated land cover because farmers planted earlier after warmer winters, and winter temperatures tended to increase during the years we studied it (Linderholm 2006). To our knowledge, this is the first evidence of human adaptation to climate change possibly affecting the phenology of wildlife.

Earlier planting after warmer winters is consistent with other studies that have found significantly earlier growing seasons in croplands after warm winters (Linderholm 2006). We did not find concomitant advances of SoGS in non-irrigated land cover. Although vegetation in these areas were also experiencing increased growing degree days, the rate of change in growing degree days was not as rapid as the rate of change in planting in irrigated land cover, resulting in habitat-specific trends in SoGS. This is likely due to farmers planting cold tolerant crop strains capable of growing in cooler environments (Kucharik 2006).

Kestrels in our study area typically have access to both irrigated and non-irrigated land covers around their nest box, but kestrel phenology throughout the study area was only associated with SoGS in irrigated land cover. Peaks in small mammal abundance in irrigated land cover have potentially advanced by 26 days since 1992, whereas, kestrels have only advanced nest initiation by 15 days. Access to non-shifting systems may reduce the selective pressure to track changes on irrigated systems, resulting in differential rates of change between SoGS and kestrels. In our area, the kestrels feeding in areas dominated by irrigated land cover primarily foraged on small mammals and insects, but kestrels feeding in areas dominated by non-irrigated land cover had a more varied diet consisting of insects, reptiles, birds, and a lower proportion of small mammals (Appendix B). However, these diet differences have no apparent effects on nest success (Heath unpub. data). For generalist species, or those feeding in heterogeneous habitats, mismatch between peaks of some prey in some areas are unlikely to have the same fitness consequences as mismatches for a specialist species (Visser & Both 2005). Alternatively, earlier prey abundance in irrigated land cover may enable kestrel response to other selective pressures on nesting phenology, such as seasonal declines in local fitness (Steenhof & Heath 2009, 2013) or competition for high-quality mates. In recent years, the earliest nesting kestrels have successfully produced two clutches of offspring (Steenhof & Peterson 1997; Heath unpub. data). This would suggest that there may be additive effects of other drivers of population change contributing to the positive association between irrigated SoGS and kestrel phenology and that kestrel reproduction rates are likely to increase with earlier nesting. However, whether increased energetic costs of raising multiple broods decreases kestrel survival is unknown.

Previously kestrel nesting phenology was described as being correlated with winter minimum temperature anomalies, and not spring temperature anomalies (Heath et al. 2012). Further, advancement in kestrel nesting phenology was hypothesized to be the result of reduced overwintering and pre-breeding constraints from warmer winters and seasonal declines in local fitness (Heath et al. 2012). By using NDVI data and focusing on the vegetation across our study area, we found that, although spring temperatures have not increased, the SoGS has advanced owing to human response to climate change. This result highlights the need for direct and reliable indicators of environmental change. Other studies of common agricultural species, such as European starlings (*Sturnus vulgaris*), have found nesting phenology to be associated with winter temperatures rather than spring temperatures (Williams et al. 2015). Given the number of wildlife species that depend on agricultural systems for portions of their annual life cycle, agricultural climate adaptations are likely to be a significant driver of biological change. Further, human activities, such as land-use change, recreation, and urbanization, which may not be climate adaptive, can act with climate change to affect species distributions, abundance, and phenology (Pautasso 2012). Eurasian blackcaps (*Sylvia atricapilla*), for example, have altered wintering behaviour and migration strategies as a result of warmer winters and backyard bird feeding (Plummer et al. 2015).

This study demonstrates the multitude of factors that have potential to contribute to changes in reproductive phenology of individual species and in broader biological systems. As human systems begin to shift in response to climate change, understanding the relationships between alterations in either or both climate and human activity will become increasingly important. This study also demonstrates the importance of

considering full annual cycles (Balbontín et al. 2009; Williams et al. 2015; Sicurella, Musitelli, Rubolini, Saino & Ambrosini 2016) when discussing climate change, as winter, not spring temperatures, predict the timing of the SoGS, especially in agricultural systems (Appendix C).

Moving Forward

It is largely unknown what effect timing of changes in prey abundance will have on those predators with access to multiple food providing systems. More research needs to be done on similar predators to determine what impacts climate change will have on the timing of events in their annual cycle. This study provides insight into at least one case of a predator with access to multiple systems tracking a single food source.

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Figures

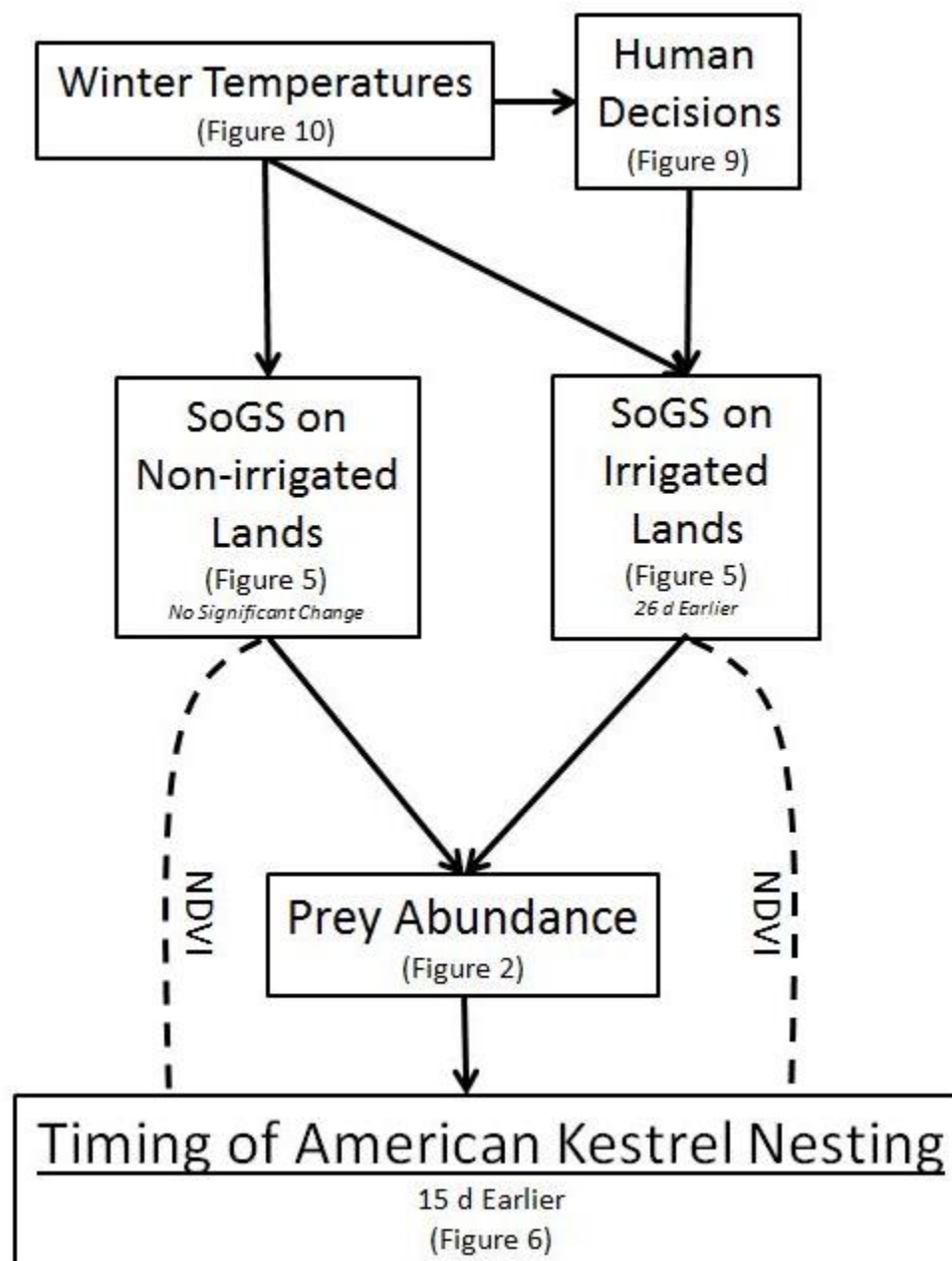


Figure 1. The schematic for the American kestrel system in southwestern Idaho, USA for 1992 to 2015. Warmer winter temperatures as well as the human decision to plant crops earlier have resulted in an earlier SoGS in irrigated land cover only. Normalized Difference Vegetation Index (NDVI) was used as a proxy for prey abundance as well as a measure of the SoGS for both irrigated and non-irrigated land covers. American kestrels are advancing their timing of nesting by 15 days in order to capitalize on the advancing peak in prey abundance occurring in irrigated land cover.

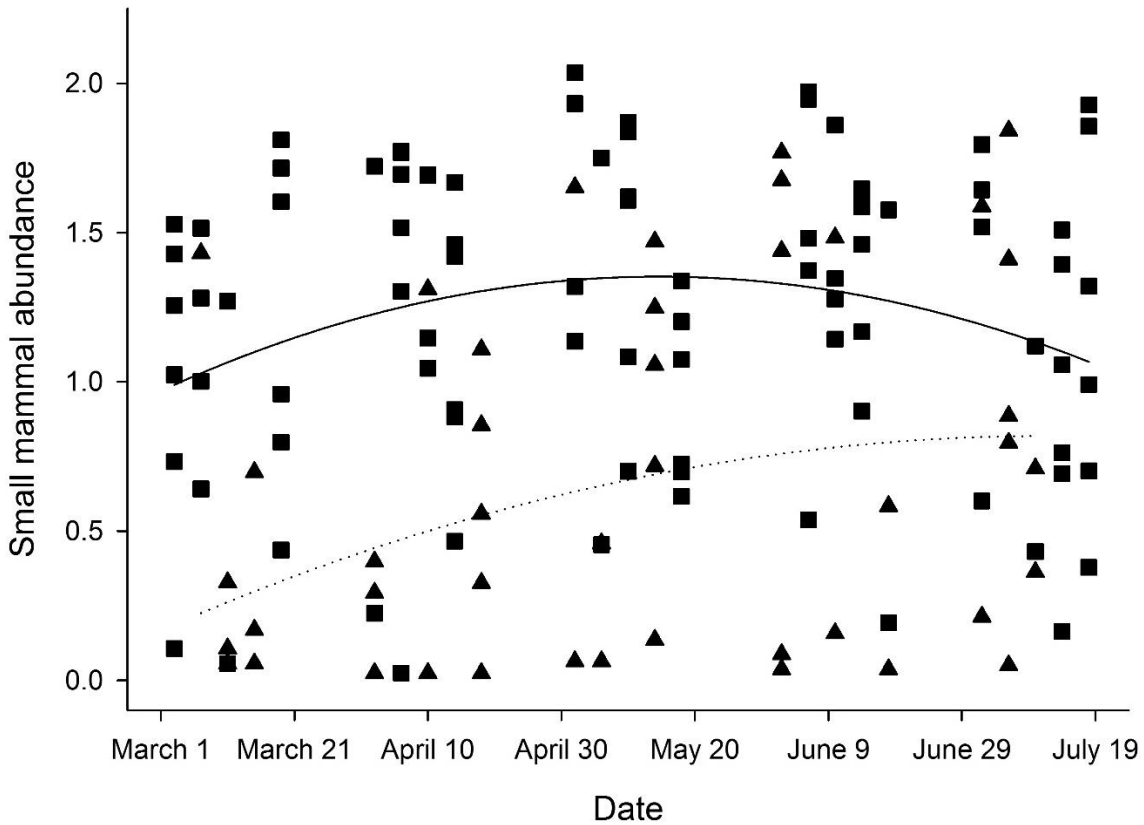


Figure 2. Small mammal abundance as a function of calendar date during 2014 for 18 plots in non-irrigated land cover (squares and solid line) and 10 plots in irrigated land cover (triangles and dashed line) in southwestern Idaho, USA. Abundance peaked in mid-May and early July for non-irrigated and irrigated land covers, respectively.

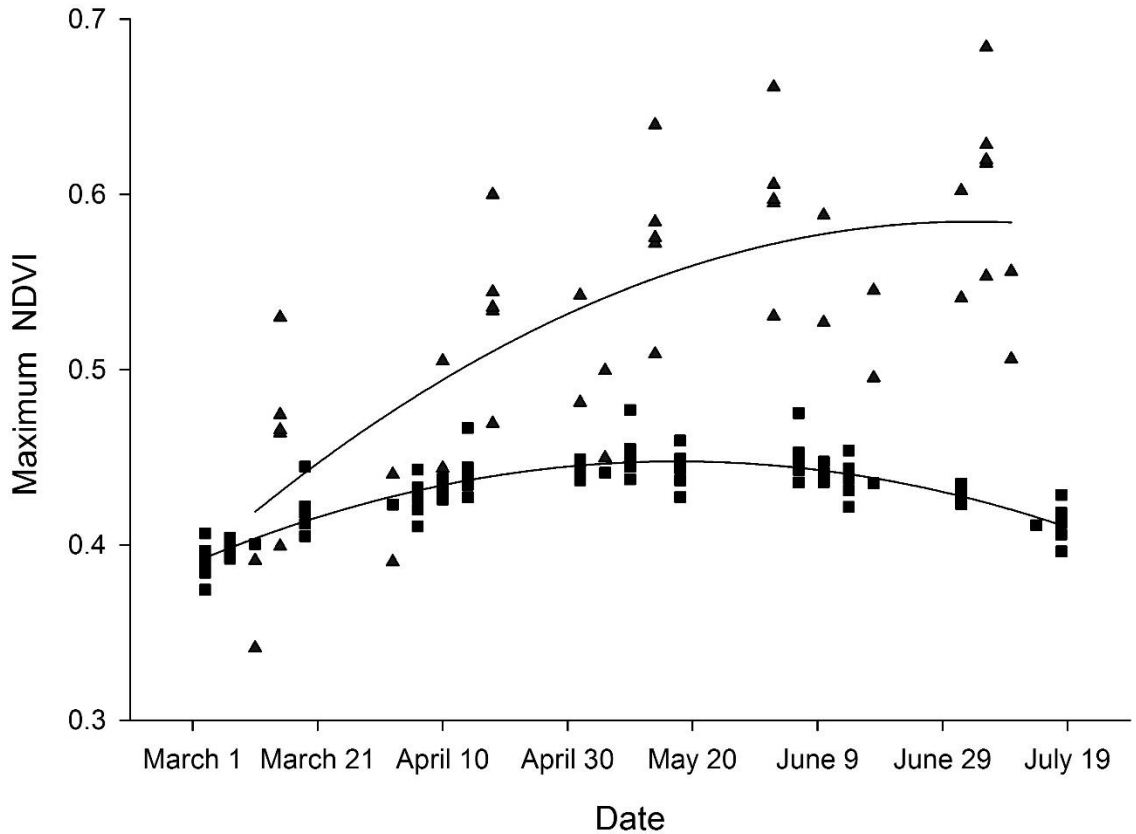


Figure 3. NDVI as a function of calendar date for 10 plots in irrigated land cover and 18 plots in non-irrigated land cover during 2014 in southwestern Idaho, USA. Non-irrigated land cover (squares) reached maximum NDVI around 10 May and differed from irrigated land cover (triangles) which reached maximum NDVI around 9 July.

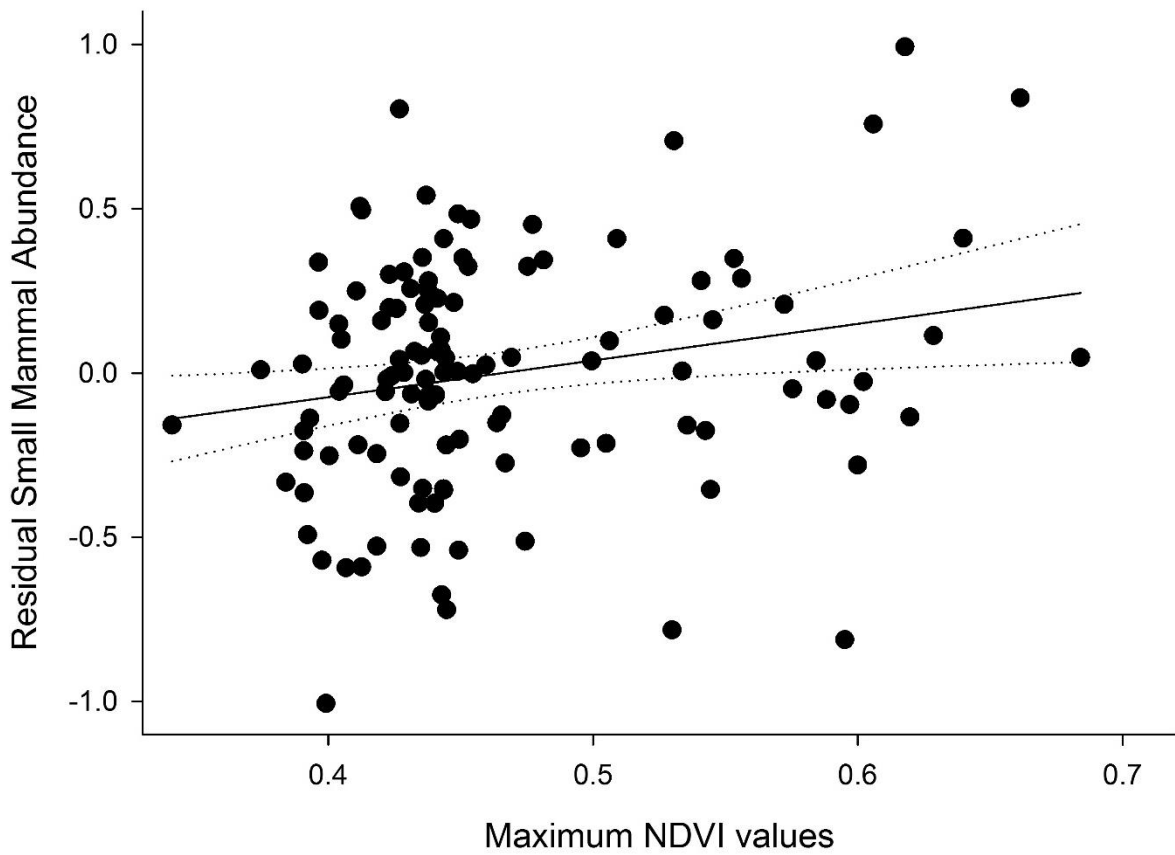


Figure 4. Relationship between monthly residual small mammal abundance (when accounting for trapping site and land cover type) and maximum NDVI in southwestern Idaho for 2014. The solid and dotted lines represent the predicted relationship and 95% confidence interval, respectively.

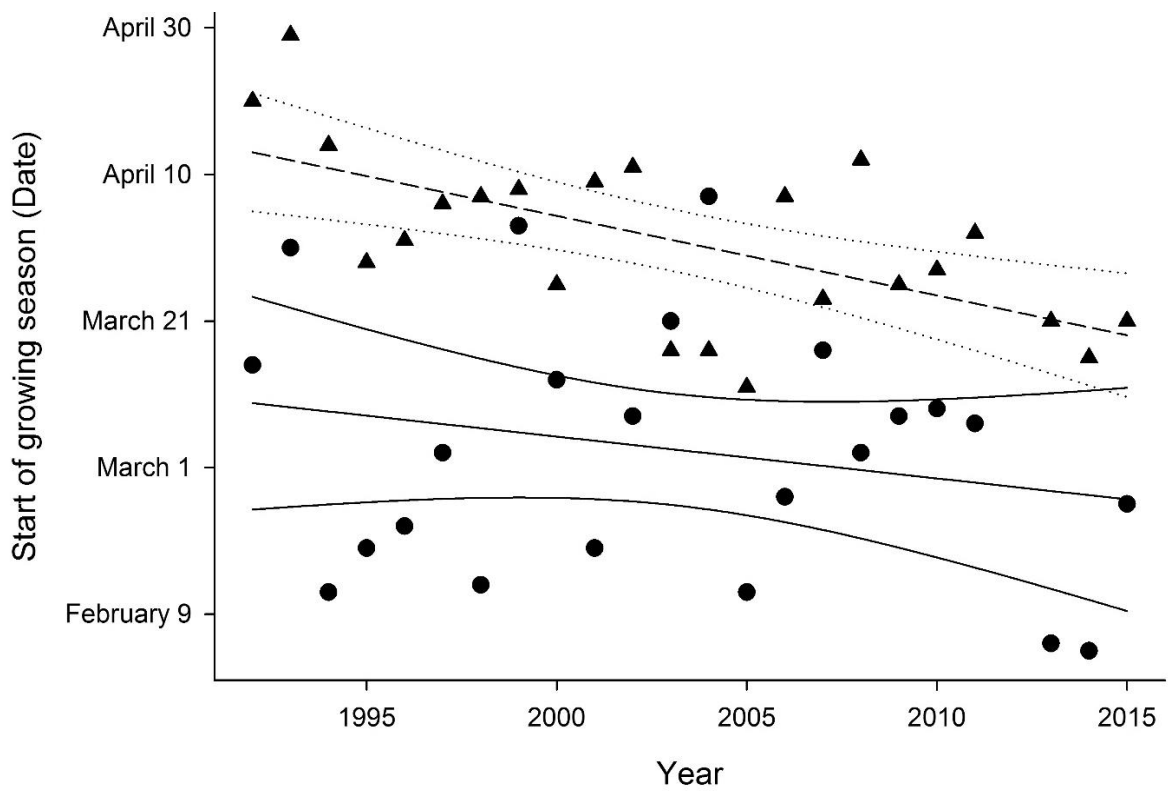


Figure 5. Relationship between SoGS and year for 1992 to 2015 in southwestern Idaho, USA. The SoGS has significantly advanced by 26 days in irrigated locations only (triangles and dashed line). The SoGS has not significantly advanced in non-irrigated locations (circles and solid line) during this same period of time. The solid and dashed lines represent the predicted relationships and the dotted lines represent the 95% confidence intervals.

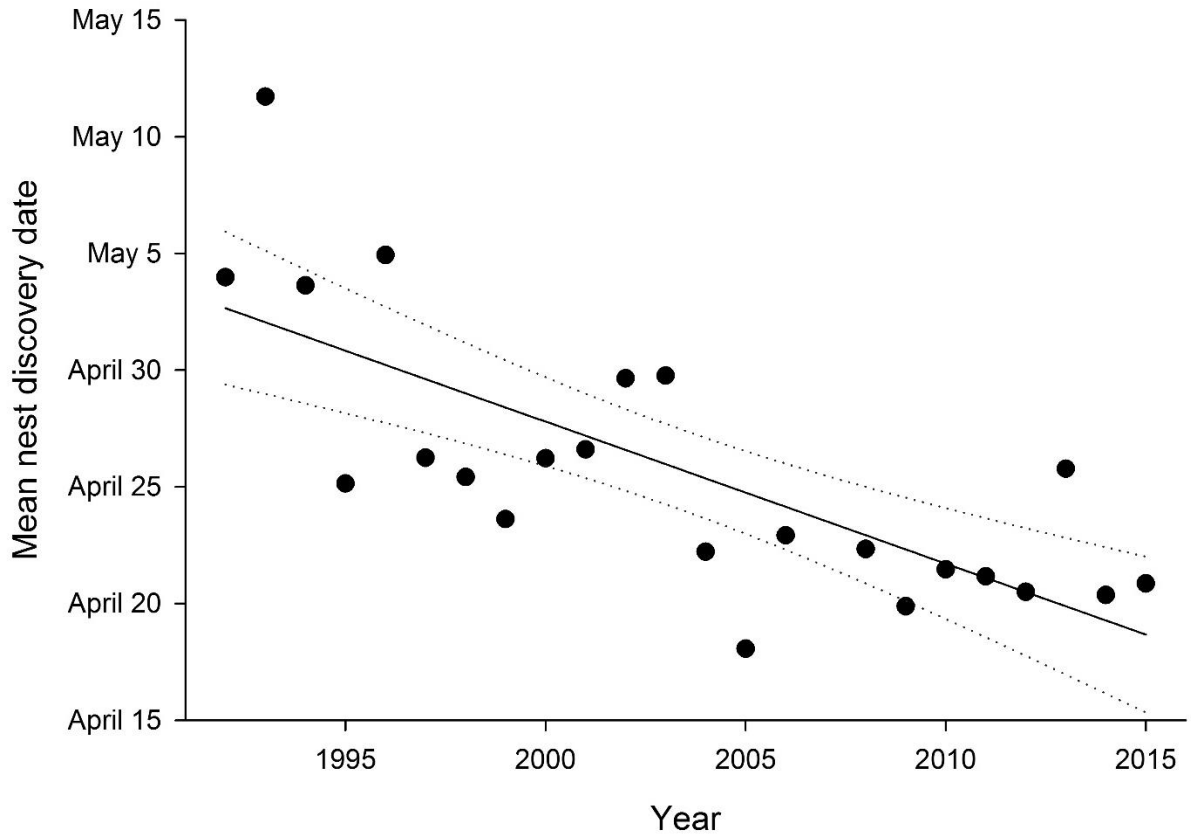


Figure 6. Relationship between American kestrel mean nest discovery dates and year for 1992 to 2015 in southwestern Idaho, USA. Nest discovery dates have significantly advanced by 15 days. Mean nest discovery date was used to represent nest initiation date because the two have been shown to be highly correlated (Steenhof & Heath 2009). The solid and dotted lines represent the predicted relationship and the 95% confidence intervals, respectively.

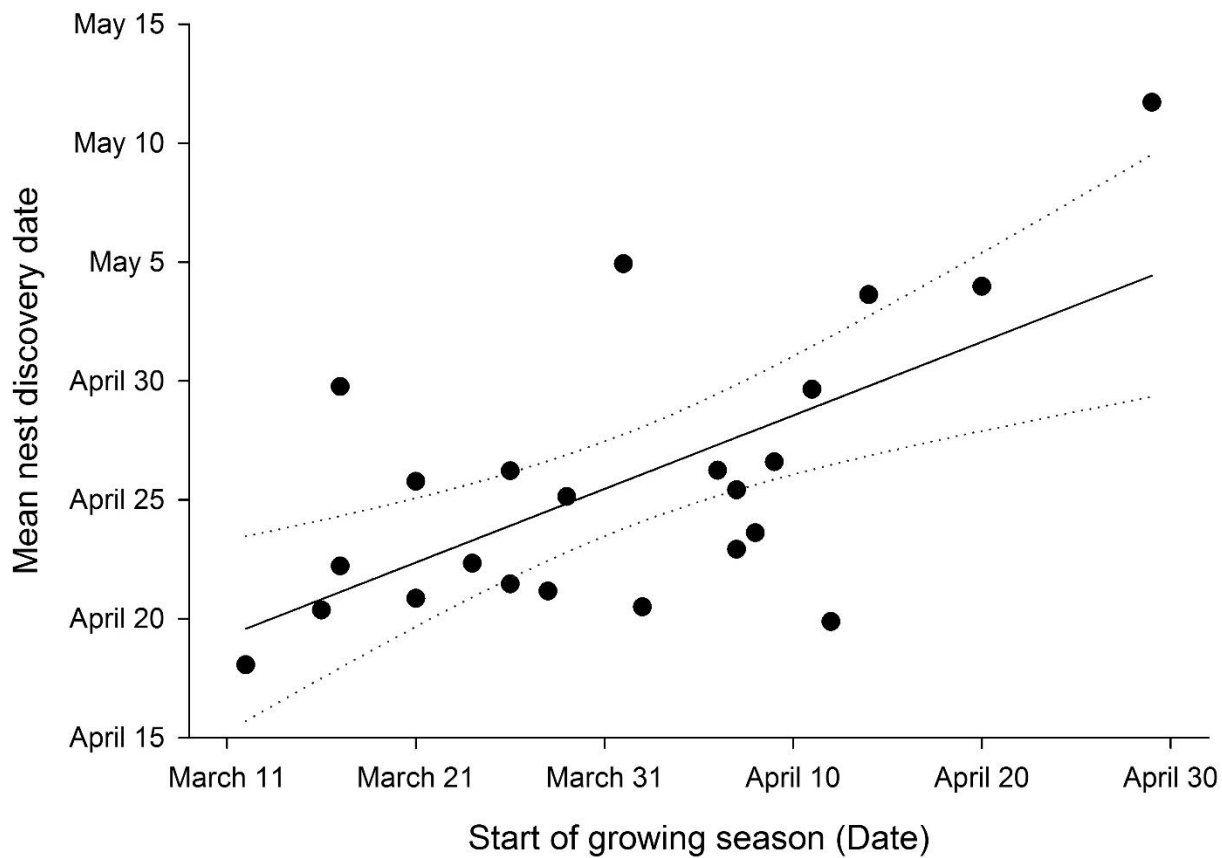


Figure 7. Relationship (and 95% confidence intervals) between American kestrel mean nest discovery date and the NDVI estimated SoGS in irrigated land cover from 1992 to 2015 in southwestern Idaho, USA.

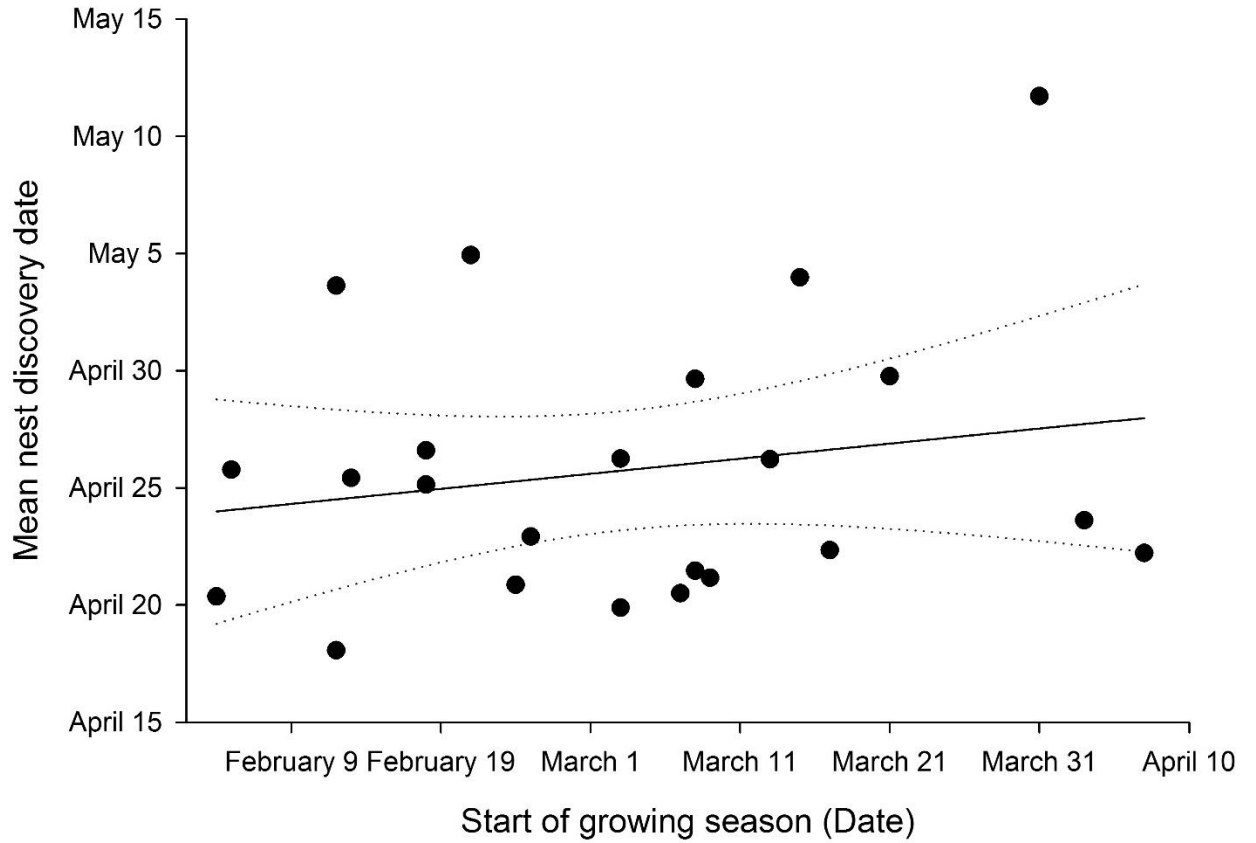


Figure 8. Relationship (and 95% confidence intervals) between American kestrel mean nest discovery date and the NDVI estimated SoGS in non-irrigated land cover from 1992 to 2015 in southwestern Idaho, USA.

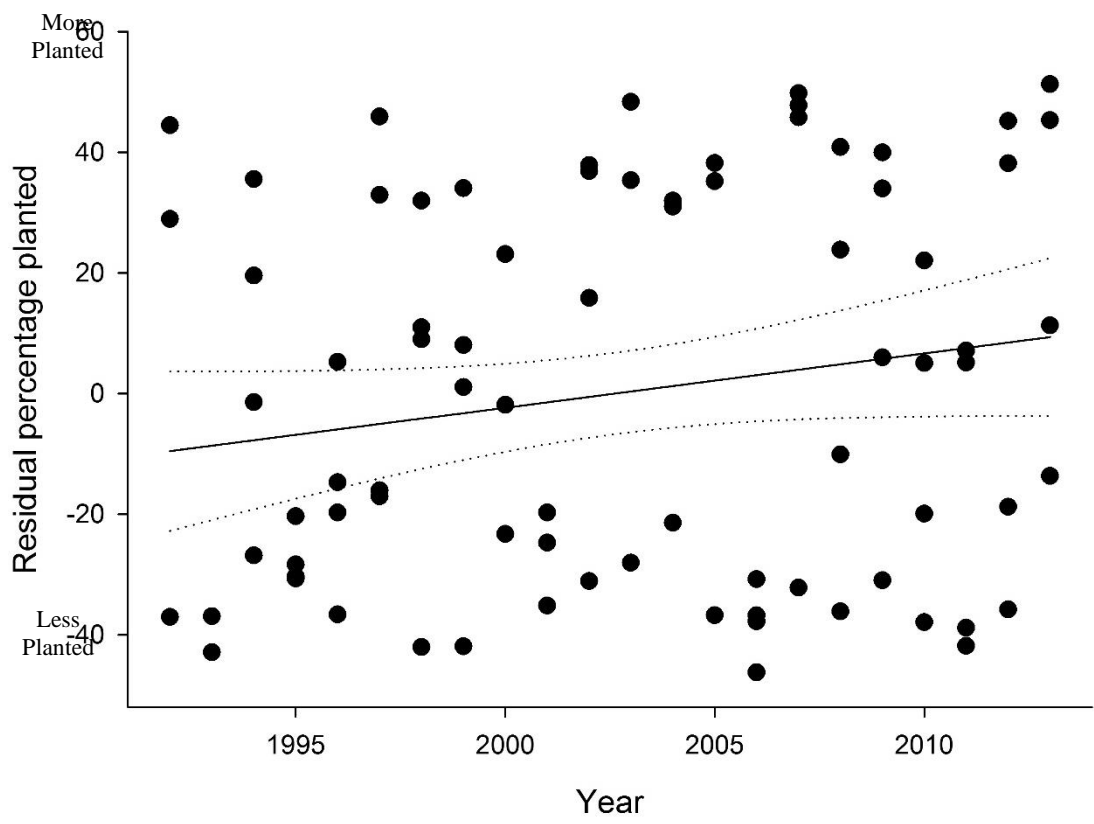


Figure 9. Relationship (and 95% confidence intervals) between the residual percentage of fields planted, when accounting for crop type and date of reporting, and year for 1992 to 2013 in southwestern Idaho, USA. Crop types included barley, potatoes, spring wheat, and sugar beets.

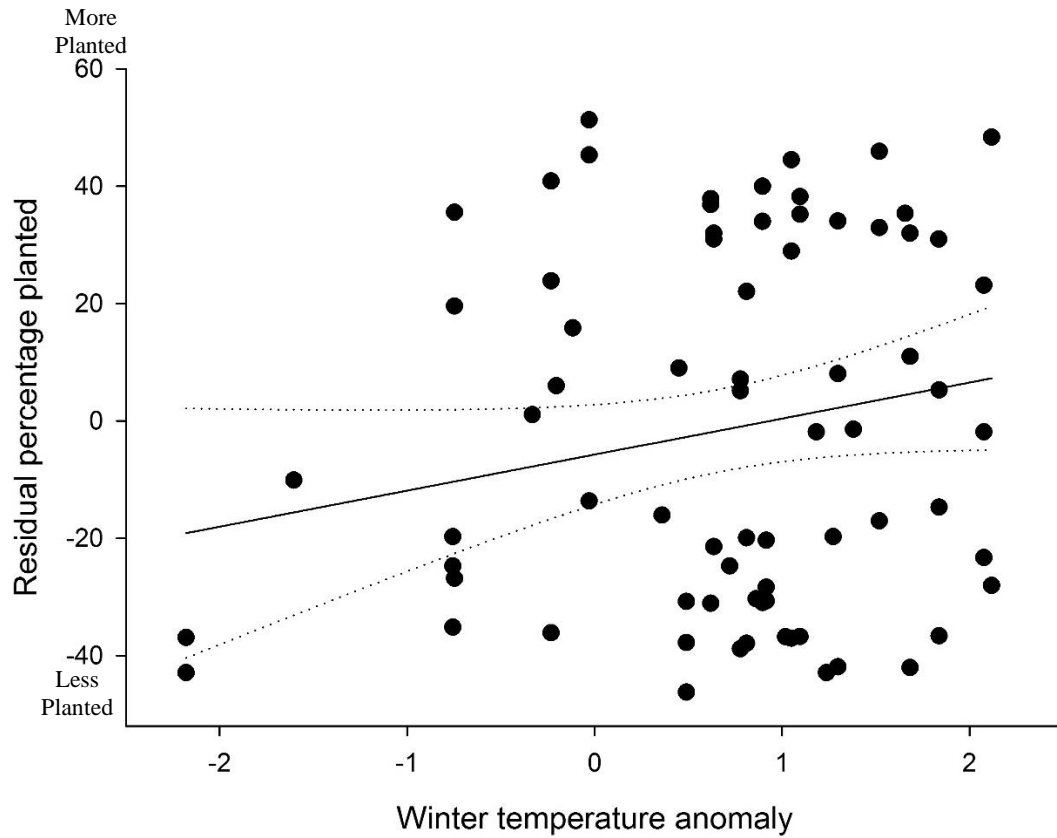


Figure 10. Relationship (and 95% confidence intervals) between the residual percentage of fields planted, when accounting for crop type and date of reporting, and winter minimum temperature anomalies for 1992 to 2013 in southwestern Idaho, USA. Warmer winter temperature anomalies resulted in a higher percentage of barley, potatoes, spring wheat, and sugar beets being planted on the first day of reporting the following spring.

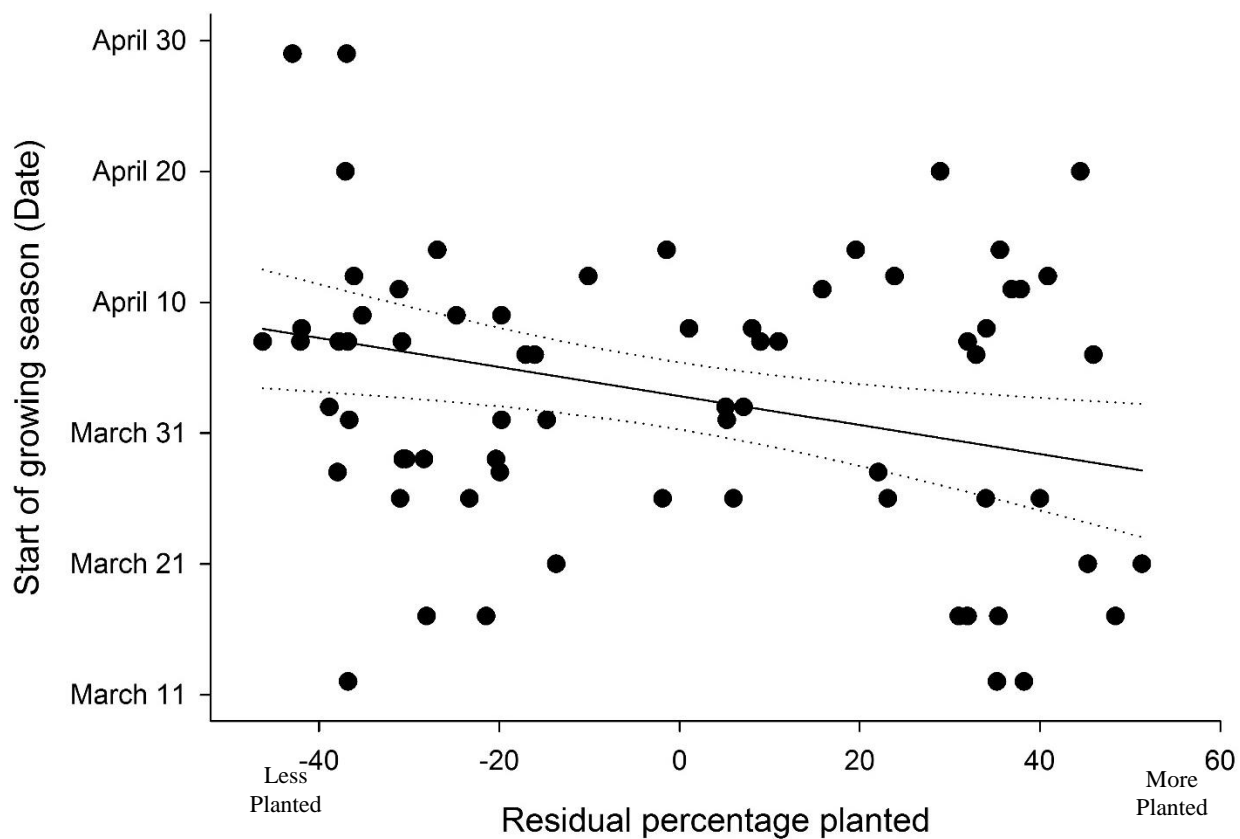


Figure 11. Relationship (and 95% confidence intervals) between SoGS and residual percentage of fields planted, when accounting for crop type and date of reporting, for 1992 to 2013 in southwestern Idaho, USA. As the proportion of fields planted by farmers in southwestern Idaho increased, the NDVI estimated SoGS significantly advanced.

APPENDIX A

Analysis of Normalized Difference Vegetation Index Data

Normalized Difference Vegetation Index (NDVI)

NDVI

Normalized Difference Vegetation Index (NDVI) is just one of many vegetation indexes that can be used in a similar fashion and is calculated on a -1 to 1 scale using Equation A1:

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{Red}) \quad (\text{Equation. A1})$$

where NIR is data from the near-infrared, and RED are data from the visible red section of the electromagnetic spectrum (Reed et al. 1994). NDVI is based on the amount of infrared and visible red light absorbed or reflected by a plant back into space (Reed et al. 1994 & Pettorelli et al. 2011). Growing, green vegetation has higher NDVI values than sparse, less photosynthetically active plants (Pettorelli et al. 2011).

Steps for obtaining and downloading Landsat imagery

For this research, NDVI values were estimated using Landsat 5 and 8 imagery, which was available for download courtesy of the U.S. Geological Survey (<http://earthexplorer.usgs.gov>, see “Steps for obtaining Landsat imagery”). Images of the study area (path 42, row 30) were taken every 16 days from 1992-2015 (except for January 2012-mid April 2013 when the Landsat 5 satellite was down until Landsat 8 satellite started). Once downloaded, Landsat images were unzipped to reveal 11 individual color bands, a copy of the image, and a metadata file (see “Steps for obtaining Landsat imagery” below).

Steps for obtaining Landsat imagery:

1. Landsat imagery can be obtained from the website <http://earthexplorer.usgs.gov/>

- You must register and request a login to obtain large amounts of data from this website. Do so before you begin by clicking “Register” at the top right corner. Always login before searching for data.

2. On the Search Criteria Tab:

- Search for our study area: enter Path 42 Row 30 in the appropriate boxes.
- You can search for specific date ranges as well. This is important when searching for long term data sets because the website only provides 100 available files at a time.

3. On the Data Sets Tab:

- Click on Landsat Archive and select appropriate Landsat satellite.

4. Click the Results icon at the bottom of the page.

5. Click the Results Tab to see all the archived files from your search.

6. Select all of the files you want to download by clicking the floppy disc icon next to each image. This will allow you to bulk download all of the files.

7. Once all files have been selected, click the “Item Basket” icon. Then click “Proceed to Checkout” and USGS will send you an email with directions for obtaining the files or you may begin downloading immediately.

Steps for downloading Landsat imagery:

1. To download the files you will need to download the Bulk Download Application (BDA) by clicking the “Bulk Download Application” link.

2. Once downloaded, open the BDA program and login. The bulk collection of files will be present after logging in.

3. Select a location on your computer to download the files to and begin downloading the files.
4. The files will download zipped and must be unzipped. To quickly unzip files, download an unzipping program such as 7-zip file manager.
5. Go to the location you downloaded your file to and unzip the file. Then unzip the file a second time in order to find the individual bands and the metadata file.

Steps for calibrating Landsat imagery

The metadata files were loaded into ENVI version 5.2 (Exelis Visual Information Solutions, Boulder, Colorado) for calibration following the steps described in Chander & Markham (2003) and revisited in Chander, Markham & Helder (2009) (see “Steps for calibrating Landsat imagery” below). The first step was to calculate radiance (L_λ) using Equation A3 (Chander et al. 2009):

$$L_\lambda = \frac{(L_{MAX\lambda} - L_{MIN\lambda})}{(Q_{calmax} - Q_{calmin})} (Q_{calmax} - Q_{calmin}) + L_{MIN\lambda} \quad (\text{eqn. A3})$$

where

L_λ = spectral radiance at the sensor’s aperture [W / (m² sr μm)]

Q_{cal} = Quantized calibrated pixel value [DN]

Q_{calmin} = Minimum quantized calibrated pixel value corresponding to $L_{MIN\lambda}$ [DN]

Q_{calmax} = Maximum quantized calibrated pixel value corresponding to $L_{MAX\lambda}$ [DN]

$L_{MIN\lambda}$ = spectral at-sensor radiance that is scaled to Q_{calmin} [W / (m² sr μm)]

$L_{MAX\lambda}$ = spectral at-sensor radiance that is scaled to Q_{calmax} [W / (m² sr μm)]

Radiance was calculated manually using the Band Math tool within ENVI and required the specific value for each of the variables which was found in the metadata file. Next, top of atmospheric (TOA) reflectance was calculated using Equation A4 (Chander et al.

2009). TOA reflectance requires $ESUN_{\lambda}$ (mean exoatmospheric solar irradiance) which was not recorded by the Landsat 8 satellites so it was estimated using Equation A5 (Department of the Interior U.S. Geological Survey 2015).

$$\rho_{\lambda} = \frac{\pi \cdot L_{\lambda} \cdot d^2}{ESUN_{\lambda} \cdot \cos \theta_s} \quad (\text{eqn. A4})$$

where

ρ_{λ} = Planetary TOA reflectance [unitless]

π = Mathematical constant equal to ~ 3.14159 [unitless]

L_{λ} = Spectral radiance at the sensor's aperture [$W / (m^2 \text{ sr } \mu m)$]

d = Earth-Sun distance (astronomical units)

$ESUN_{\lambda}$ = Mean exoatmospheric solar irradiance [$W / (m^2 \mu m)$]

θ_s = Solar zenith angle [degrees⁹]

$$ESUN = (\pi \cdot d^2) \cdot \frac{(\text{Radiance Maximum})}{(\text{Reflectance Maximum})} \quad (\text{eqn. A5})$$

where

π = Mathematical constant equal to ~ 3.14159 [unitless]

d^2 = Earth-Sun distance (astronomical units)

Steps to calibrate files in ENVI:

1. Open ENVI (64-bit).
2. Go to "File" and select "Open"
3. Select the desired metadata file to be calibrated.
 - To read the metadata file name to determine date:

LC80420302013108LGN01_MTL

LC8 means Landsat 8, could be LC5 for Landsat 5

Year: LC80420302013108LGN01_MTL

Julian Date: LC80420302013108LGN01_MTL

4. Search for the Band Math tool in the Toolbox search option.

5. To calculate Radiance: $[(\text{radiance max}-\text{radiance min})/(\text{qcal max}-\text{qcal min})*(\text{band\#} - 1 + \text{radiance min})]$

- For Landsat 5, enter:

Band 3: $((264.0+1.170)/254)*(B3-1)-1.170$

Band 4: $((221.0+1.510)/254)*(B4-1)-1.51$

- For Landsat 8, enter:

Band 4: $((\text{radiance_max_band_4}-\text{radiance_min_band_4})/65534)*(B4-1) + \text{radiance_min_band_b4}$

Band 5: $((\text{radiance_max_band_5}-\text{radiance_min_band_5})/65534)*(B5-1) + \text{radiance_min_band_b5}$

- Note:

1. *Radiance maximum and radiance minimum can be found in the metadata file.*

6. Click “OK” and it will say that B3 or B4 is an unknown variable. You must select the correct band number within the Landsat file you just uploaded.

7. Save the file.

8. To calculate Reflectance:

- For Landsat 5, enter:

Band 3: $(\pi*B3*(\text{Earth Sun Distance})^2)/(ESUN * \cos((90-\text{sun elevation})*\pi /180))$

Band 4: $(\pi *B4*(\text{Earth Sun Distance})^2)/(ESUN* \cos((90-\text{sun elevation})*\pi /180))$

- Notes:

1. *ESUN for Landsat 5 was provided by Chander & Markham (2003):*

Band 3: 1536

Band 4: 1031

2. *Earth sun distance and sun elevation are found in the metadata file.*

3. *When asked to select B3 and B4, select the bands corrected for radiance.*

- For Landsat 8, enter:

Band 4: $(\pi * B4 * (\text{Earth Sun Distance})^2 / \text{ESUN} * \cos((90 - \text{sun elevation}) * \pi / 180))$

Band 5: $(\pi * B5 * (\text{Earth Sun Distance})^2 / \text{ESUN} * \cos((90 - \text{sun elevation}) * \pi / 180))$

- Notes:

1. *ESUN was not collected for Landsat 8 and must be estimated using equation:*

*$ESUN = (\pi * d^2) * \text{radiance maximum} / \text{reflectance maximum}$*

2. *When asked to select B3 and B4, select the bands corrected for radiance.*

3. *When asked to select B4 and B5, select the bands corrected for radiance.*

Steps for calculating NDVI and extracting NDVI values from ArcGIS

NDVI was calculated using the Band Math tool in ENVI instead of the NDVI tool provided in order to insure that correct reflectance files were used (see “steps for calculating NDVI” below). NDVI was calculated using Equation A6 for Landsat 5 images and Equation A7 for Landsat 8 images because the NIR and Red bands changed in number when satellite 8 started.

$$\text{NDVI} = (\text{Band 4} - \text{Band 3}) / (\text{Band 4} + \text{Band 3}) \quad (\text{eqn. A6})$$

where

Band 4 = Near-infrared Light

Band 3 = Visible Red Light

$$\text{NDVI} = (\text{Band 5} - \text{Band 4}) / (\text{Band 5} + \text{Band 4}) \quad (\text{eqn. A7})$$

where

Band 5 = Near-infrared Light

Band 4 = Visible Red Light

Once NDVI files were created in ENVI, they were saved as TIFF files so that they could easily be imported into ArcGIS 10.1 (Esri 2012, Redlands, CA). ArcGIS 10.1 was used to draw a polygon that represented our 1000 km², irregularly shaped study area. The GPS locations of 71 kestrel nest boxes were imported into ArcGIS 10.1 and landscape type was classified as irrigated or non-irrigated, resulting in 37 irrigated and 34 non-irrigated locations. The nest boxes selected were at locations in which no land use change had taken place during our study period. An 80 x 70 m polygon was drawn directly in front of the kestrel nest box to represent the area where prey surveys were conducted in 2014. This established NDVI values and local prey abundance values as the same spatial scale.

Each NDVI image was visually examined to determine if cloud cover was present and potentially impacting the underlying NDVI value. The image was not used if >25% of the study area was obscured by clouds. If <25% of the study area was covered by clouds, each individual 80 x 70 m site was examined to determine if it was obscured. The NDVI data was thrown out if the individual site was obscured in any way. Maximum NDVI values were extracted for each individual site. We selected maximum NDVI values because minimum values can be contaminated by cloud cover and ground conditions (Pettorelli et al. 2005 & Bradley et al. 2007). All maximum NDVI values were

grouped based on vegetation type and Julian date. The highest maximum NDVI value within each vegetation type was considered the NDVI value for that Julian date.

Steps to calculate NDVI:

1. For Landsat 5, enter: $(B4-B3)/(B4+B3)$

- Note:

1. Band 3 and 4 must be the reflectance bands you just made.

2. For Landsat 8, enter: $(B5-B4)/(B5+B4)$

- Note:

1. Band 5 and 4 must be the reflectance bands you just made.

3. Once the NDVI tile appears, go to File-> Save as -> Save as... (ENVI, NITF, TIFF, DTED). Then select the NDVI file you just made, click ok. Click the “output Format” and select TIFF. TIFF files are easily loaded in ArcGIS.

Steps for getting NDVI values from ArcGIS:

1. Open ArcGIS and create a study area shape file or individual locations where NDVI is to be examined. If using individual locations, be sure to name them appropriately and combine all shape files into one large file. This will reduce the need to extract NDVI from each individual location.

2. Add the NDVI TIFF file created in ENVI to ArcGIS by selecting “Add Data” and following prompts.

3. To extract NDVI values, use the “Zonal Statistics as Table” tool. Fill in the blanks as follows:

- Input raster or feature zone data: Use the study area or file of multiple small sites.

- Zone field: If you have renamed your small sites you will select the column header that applies to your column of site names.
- Input value raster: Use the NDVI TIFF file to be analyzed.
- Output table: Properly name the file and provide a pathway to the folder where it will be saved.
- Uncheck “Ignore NoData in calculations [optional]” if desired.
- Leave the Statistics type (optional) as “ALL” to get minimum, maximum, range, etc.

4. Click “OK”.

5. Open the file that appears in the workspace by right clicking it and selecting “Open”.

6. Export the file by selecting the “Export” option at the top left corner of the window.

- Note:

1. Be sure to save file as a text file because it is easier to import into Excel.

Interpolating missing data and estimating the Start of the growing season (SoGS)

Long term NDVI series often experience missing data values due to cloud contamination, unavailable files, or irregular sampling intervals. Over the years a number of methods for interpolating or correcting data have been used (Reed et al. 1994; Brown et al. 2006; Bradley et al. 2007, Hermance, Jacob, Bradley & Mustard 2007; Jönsson & Eklundh 2002; Brooks et al. 2012). This study used a combination of approaches to fill missing data. When missing two data points or less, linear interpolation was used to fill the missing data. A third order harmonic regression analysis that was trained by the year before and the year after was used to generate an average annual NDVI curve. If the values were less than the next known NDVI value, the annual curve values were used to

replace missing data gaps (Brooks et al. 2012). At times the third order harmonic regression was influenced by large data gaps and would estimate erroneously high NDVI values. Annual curve values were not used if they were greater than adjacent known NDVI values because erroneous maximums could influence the start of the growing season (see below). This resulted in a few remaining data gaps that were replaced by weekly averages of known NDVI values.

A number of methods have been developed to determine seasonal phenology of vegetation using NDVI data. Early methods included establishing a minimum NDVI threshold value. The start of the growing season (SoGS) was then classified as the day NDVI was greater than the minimum threshold value, but the threshold varied by vegetation type, soil background, and light conditions (Reed et al. 1994). A more popular method involves Gaussian statistics and using the date NDVI reaches 10% of the yearly max as the SoGS (Jönsson and Eklundh 2002). We chose not to use this method because the high difference in NDVI values between irrigated and non-irrigated land cover. Irrigated land cover has a much higher range of NDVI values and would reach 10% of maximum NDVI very early in the season while NDVI values in non-irrigated land cover do not change much throughout the season and would therefore take much longer to reach 10% of maximum. We selected the method described by Reed et al. (1994) in which a three day moving average curve was imposed on the annual NDVI curve. The date the moving average crossed the annual curve was considered the SoGS because it signifies the date NDVI makes a sudden increase and could be explained by photosynthetic activity. We used SigmaPlot 12.0 (Systat Software, Inc., San Jose, CA, USA) to plot the annual curves and impose the moving average (Figures A1 & A2).

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Figures

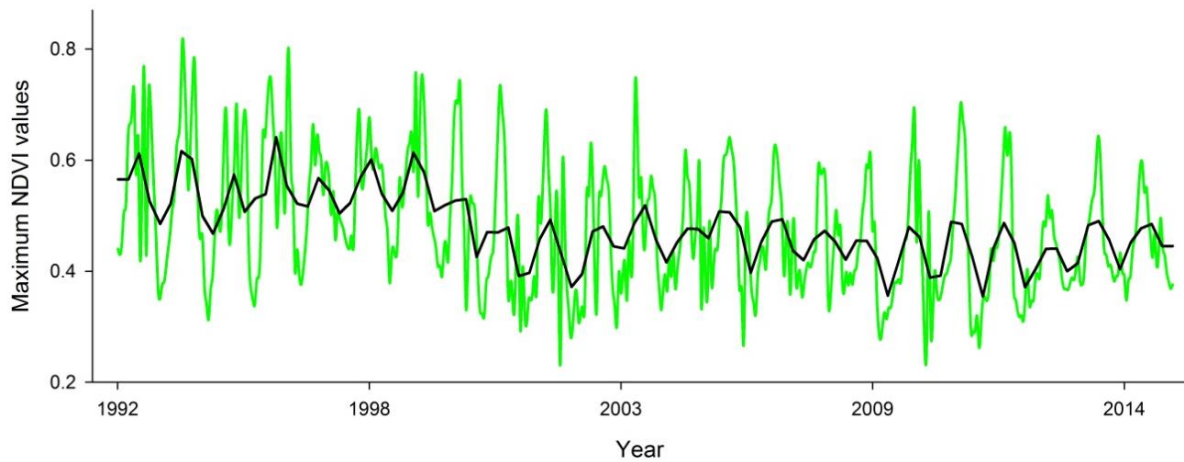


Figure A1. We used Landsat 5 and 8 imagery to calculate maximum NDVI values for our study area for years 1992 to 2015 (excluding 2012). We constructed an annual maximum NDVI curve (in green) using a mix of approaches and imposed a three day moving average (in black) to calculate the SoGS in non-irrigated land cover (Reed et al. 1994).

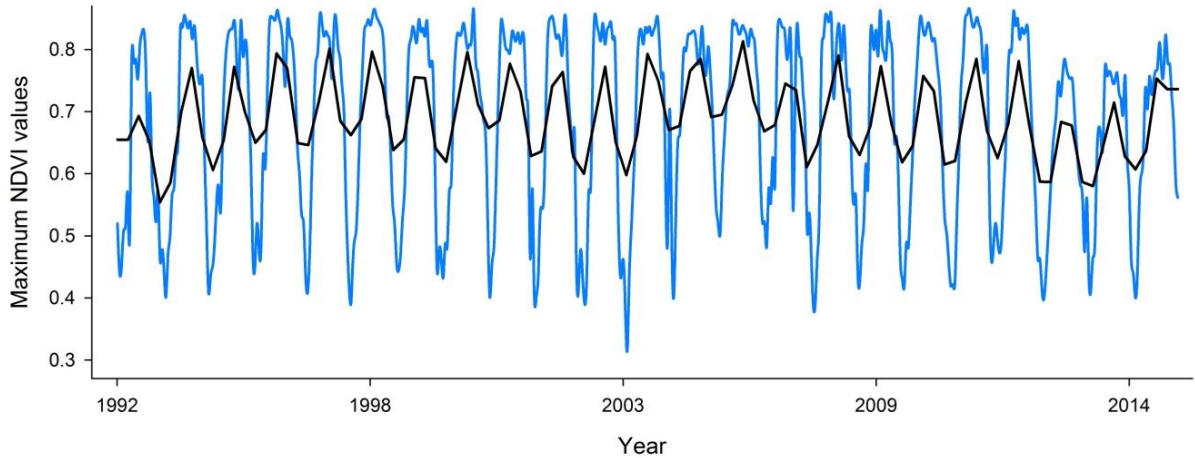


Figure A2. We used Landsat 5 and 8 imagery to calculate maximum NDVI values for our study area for years 1992 to 2015 (excluding 2012). We constructed an annual maximum NDVI curve (in blue) using a mix of approaches and imposed a three day moving average (in black) to calculate the SoGS in irrigated land cover (Reed et al. 1994).

APPENDIX B

Nest Camera Use for Diet Validation

Nest Camera Methods

We installed Spy on a Bird LLC cameras (model IP 207W, Winston Salem, NC, USA) in five different nest boxes to confirm that the prey species sampled with track plates were important components of the kestrel's diet. Two cameras were installed in nest boxes on irrigated land cover, and three on non-irrigated land cover. The cameras were installed once the chicks hatched and prey deliveries started and cameras remained in place until after all chicks fledged. Cameras were mounted inside either the top or side of the nest box depending on how the box opened. The camera was connected to a battery via a wire that ran out of the nest box and down to a deep-cycle marine battery buried in the ground below the nest box. The cameras were programmed to record any movement that occurred and picked up the adult making prey deliveries. All video files were stored on a 32GB micro SD card to be reviewed at a later time. Nest boxes were visited every 2-3 days to change the battery and the micro SD card. Prey items were scored as follows: vole, deer mouse, bird, lizard, cricket, cicada, beetle, grasshopper, or unknown. The animals were classified using the following characteristics: mammals: tail length, size, and color; birds: presence of feathers and anisodactyl feet; lizard: presence of scales, skin pattern, and body shape, tail length; invertebrates: size, color, wing length, leg length, and presence of antennae.

Analysis of Nest Camera Data

To determine the relevance of surveyed prey to kestrel diet we calculated the Shannon's Index to assess biodiversity and compared biodiversity indices between irrigated and non-irrigated locations using a t-test (Marti, Bechard & Jaksic 2007).

Nest Camera Results

A total of 5,000 one-minute-long video files were collected from 5 nest boxes in 2014. Feeding events made up 350 of these segments and included 663 prey items, but only 376 were successfully categorized. Items were often unidentifiable due to how quickly they were consumed or there was no clear view of item during the prey exchange between parent and offspring. Of the 376 identifiable prey items, grasshoppers made up 39%, small mammals made up 34%, cicadas made up 12%, lizards made up 6%, beetles made up 5%, and birds and crickets each made up 2%. We found that prey diversity differed significantly between non-irrigated and irrigated locations (Two-sample t-test: $t_3 = 3.75$, $P = 0.03$). Prey items in non-irrigated locations were much more diverse and included items that were not seen in irrigated locations, but both locations primarily consisted of small mammals and insects (Figures B1 and B2).

References

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Figures

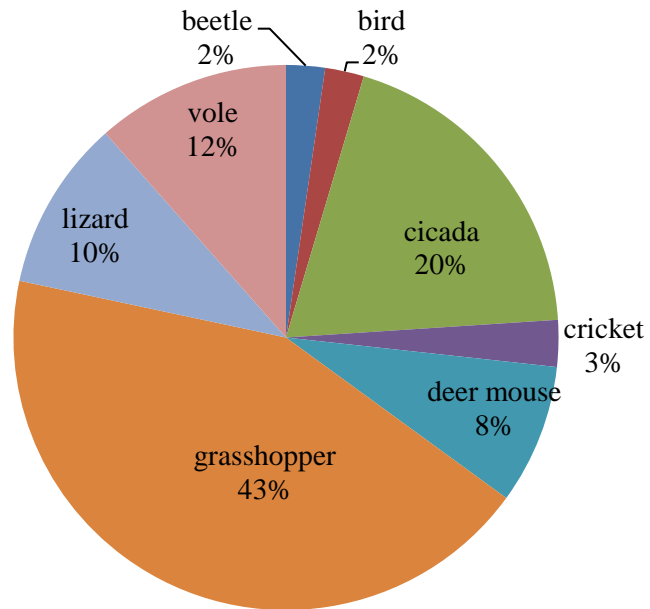


Figure B1. Prey consumption in three nest boxes by American kestrels in non-irrigated landcover in southwestern Idaho, USA for 2014. Prey items consumed varied more and included prey items not observed in irrigated land cover (Figure B2).

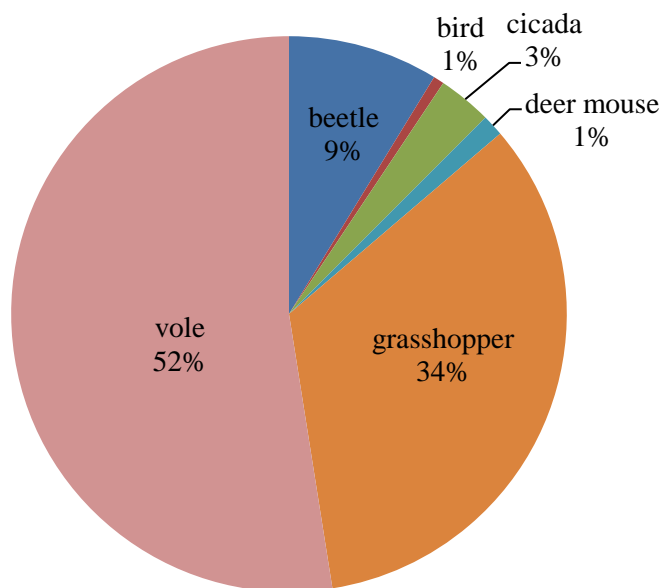


Figure B2. Prey consumption in two nest boxes by American kestrels in irrigated land cover in southwestern Idaho, USA for 2014.

APPENDIX C

Crop Phenology and the New York Canal

Weather and Irrigation Affect Crop Phenology

The impact of climate change on plant phenology has received much attention because of its ties to agriculture and human food resources. Climate change ultimately affects human survival through higher temperatures, droughts, floods, rain fall changes affecting food security around the world (Tripathi, Tripathi, Chauhan, Kumar & Singh 2016). As human populations continue to increase, agriculture will need to provide food and fiber to meet the increased demand while facing altered climate and depleted natural resources (Anwar, Liu, Macadam & Kelly 2013).

With humans and climate change both capable of altering systems, it is important to understand the specific drivers bringing about change. Changes in crop production such as earlier planting or using different crop strains are very important to understand because they may affect surrounding natural systems (Schwartz et al. 2006). Therefore, alternative farming practices, especially earlier planting of crops, may result in resources being available earlier in the year and potentially affecting aspects of phenology.

As shown above, American kestrel nesting phenology in southwestern Idaho has advanced by 15 days from 1992 to 2015. This advancement is linked to the start of the growing season (SoGS) on irrigated land cover only, which has advanced by 26 days from 1992 to 2015. It is possible that the New York Canal, one of the major irrigation canals providing water for much of the farming area within our study site, has advanced the release of irrigated water over the last 24 years. Farming in Idaho is also heavily reliant on available ground water from snowmelt, which we know to have occurred 9 days earlier between 1980 and 2007 in the local Boise National Forest (Kunkel & Pierce 2010). We were interested in determining if warmer springs or an increase in growing

degree days (GDDs, calculated by adding each day's maximum and minimum temperatures divided by two and subtracting an established base) affected the timing of crop planting by local farmers. We were also interested in determining if the cutting of alfalfa advanced as a result of warmer winter temperatures, warmer spring temperatures, an earlier (SoGS), or a an increase in growing degree days (GDDs), as well as determining if the release of irrigation water from the New York Canal has changed over time potentially facilitating earlier planting of crops or cutting of alfalfa.

Methods

We obtained Idaho Crop Progress and Condition reports from the USDA National Agricultural Statistics Service for 1992-2013. In 2014 the USDA stopped reporting region specific data and transitioned to statewide data so years 2014 and 2015 were excluded from our analysis. Previous research used the date 10% of a crop was planted as the initial planting date, but our data rarely included 0% values and first recorded values were often near 50% (Kucharik 2008). Therefore, we examined the first reported date of planting for barley, potatoes, spring wheat, and sugar beets as well as the first, second, and third cutting of alfalfa. Spring and winter temperature anomalies were used to detect if seasonal temperature changes affected crop planting or the cutting of alfalfa (see above for anomaly information). Winter months were November to February to coincide with the months when overwintering kestrels were present and spring months were March and April to coincide with the months when migratory birds arrive from overwintering areas and initiate nests (Crick & Sparks 1999; Both et al. 2010; Heath et al. 2012).

We obtained canal water release values from the Idaho Department of Water Resources Water Rights Accounting Department for the New York Canal. As canal water

was released, the daily mean values of discharge in cubic feet per second were recorded. Zero values were recorded when no water was released and values quickly reached 1000 ft³/second once irrigation began. We classified the date that irrigation began as the date when values were greater than 1000 ft³/second were recorded. In years of high snowmelt runoff, water was released at rates typically less than 1000 ft³/second for a period of time before irrigation began. There were some years when water was released for runoff and there was no period of time when water was shut off before irrigation began, but the water discharge dramatically dropped before irrigation began. In those years we considered the start of irrigation to be the first date discharge was greater than 1000 ft³/second after a period of low values occurred.

We used linear models to determine if the percent of land planted with each crop was higher earlier in the year from 1992 to 2013. All crop types were combined within a single linear model and we used crop type, initial reporting date, and year to examine whether the proportion of land planted at initial reporting had changed over time. The predictor variables spring temperature anomaly and GDDs, instead of year, were used to examine whether the proportion of land planted with a crop depended on spring weather or GDDs. In additional linear models, all cutting events were combined and the initially reported percent of cutting events were predicted by cutting event number, initial reporting date, and the variable of interest. Winter temperature anomaly and SoGS were analyzed for years 1992-2013 (excluding 2007). GDD analyses were for years 1992-2011 (excluding 2007). Spring temperature anomaly analyses were for years 1992-2009 (excluding 2007).

Linear models were also used to determine if the start of irrigation has changed over time. In the linear models, the start of irrigation was predicted by the year. Years 1995 and 2015 were excluded from the analysis because there was no definite transition between snowmelt runoff and the start of irrigation. Year 2010 data was unavailable and therefore not included in the analysis. All analyses were performed in R v. 3.1.1.

Results

Spring temperature anomalies did not predict the percentage of crops planted on the first day of reporting ($\beta = -0.78 \pm 3.28$, $F_{1,60} = 0.057$, $P = 0.813$) suggesting that winter temperatures have a greater effect on the date of crop planting than spring temperatures (see above). The percent of planted crops reported on the first day increased as the number of GDDs increased ($\beta = 0.086 \pm 0.026$, $F_{1,68} = 10.9$, $P < 0.002$). The cutting of alfalfa reported at the beginning of each cutting event followed similar patterns as crop planting (see above), with the exception of spring temperature anomalies.

Warmer winter temperature anomalies resulted in a higher percentage of alfalfa fields being cut at the beginning of each cutting session, but not significantly ($\beta = 1.89 \pm 1.96$, $F_{1,54} = 0.923$, $P < 0.341$). When spring temperature anomalies were warmer, more alfalfa was cut at the beginning of each session ($\beta = 5.143 \pm 2.23$, $F_{1,45} = 5.11$, $P < 0.029$). The percent of alfalfa being cut at the beginning of each session increased as the number of GDDs increased, but not significantly ($\beta = 0.086 \pm 0.026$, $F_{1,51} = 0.498$, $P < 0.484$). Less alfalfa was cut at the beginning of each session when the SoGS occurred later in the year, but not significantly less ($\beta = -0.11 \pm 0.19$, $F_{1,54} = 0.326$, $P < 0.57$). The start of irrigation from the New York Canal did trend earlier, but was not significant ($\beta = -0.39 \pm 0.32$, $F_{1,19} = 1.51$, $P < 0.24$, Figure C1).

Discussion

We were interested in determining if farming practices advanced as a result of warmer winter temperatures, warmer spring temperatures, earlier SoGSs, or an increase in GDDs. We used USDA Crop Progress and Condition Reports from 1992-2013 to monitor the initially reported percent planted of barley, potatoes, spring wheat, and sugar beets, as well as the initially reported percent alfalfa that had been cut at the beginning of each of the three alfalfa cutting sessions. We found that spring temperature did not predict the percentage of crops planted. We also found that the percent planted increased as the number of GDDs increased. Spring temperature anomalies had a more significant impact on the cutting of alfalfa than winter temperatures or the number of GDDs. Spring temperatures may be more important to the alfalfa because the crop is already in the ground and begins to grow as spring temperatures warm. We also found that the New York Canal, while not significantly so, has released irrigation water 9.2 days earlier over the last 24 years. This earlier release of irrigation water may facilitate the earlier planting of many crops across our study area.

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Figures

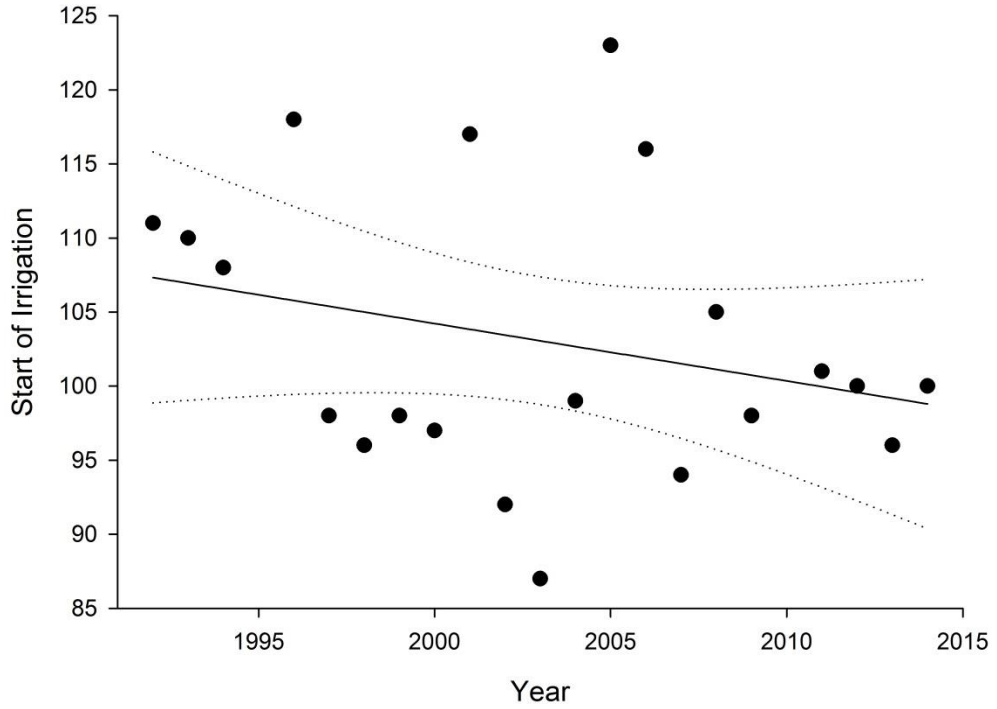


Figure C1. Relationship (and 95% confidence interval) between start of irrigation and year for 1992 to 2015 in southwestern Idaho, USA. The release of irrigation water from the New York Canal in southwestern Idaho has not significantly advanced but trended towards a 9.2 day advancement indicating that farmers are gaining access to irrigation water earlier in the year.