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Sensitivity of summer stream temperatures to climate variability and riparian reforestation strategies

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ABSTRACT

Study region: The Salmon River is the second largest tributary of the Klamath River in northern California, USA. It is a region of steep mountains and diverse conifer forests. Historical land uses including logging, flow diversions, and hydraulic gold mining, have resulted in altered sediment transport regimes, diminished riparian cover and reduced large woody debris. These in turn have altered the thermal regime of the river. Summer stream temperatures commonly exceed salmonid (specifically *Oncorhynchus* spp.) temperature thresholds.
Study focus: Thermal dynamics of a one-kilometer reach of the Salmon River was quantified using distributed temperature sensing fiber-optics (DTS) and *Heat Source* modeling. Stream thermal responses to scenarios of air temperature increase and flow reduction were compared with riparian reforestation simulations to estimate benefits of reforestation.
New hydrological insights: Elevated air temperatures (2 °C, 4 °C, 6 °C) increased mean stream temperature by 0.23 °C/km, 0.45°C/km and .68 °C/km respectively. Reforestation lowered temperatures 0.11–0.12 °C/km for partial and 0.26–0.27 °C/km for full reforestation. Reduced streamflow raised peak stream temperatures in all simulations. Warming could be mitigated by reforestation, however under severe flow reduction and warming (71.0 % reduction, 6 °C air temperature), only half of predicted warming would be reduced by the full reforestation scenario. Land managers should consider reforestation as a tool for mitigating both current and future warming conditions.

1. Introduction

Stream temperature plays a critical role in determining the overall structure and function of stream ecosystems. Temperature directly affects the distribution of fish (Meisner, 1990; Berman and Quinn, 1991; Eaton and Scheller, 1996; Welsh et al., 2001), metabolic and overall growth rates of aquatic organisms (Markarian, 1980; Gregory et al., 2000), and the abiotic conditions – such as gas solubility and solute concentration – that surround them (Matthews and Berg, 1997). Aquatic fauna are particularly vulnerable to changes in the magnitude and duration of elevated stream temperatures due to their limited mobility in the stream environment.

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Previous research has shown that land management practices both directly and indirectly affect stream temperature. For example, regulated flows have changed the magnitude and extent of peak temperature downstream (Lowney, 2000). Logging and livestock grazing have modified the quantity and quality of riparian vegetation, which buffer the stream from incoming solar radiation (Brown and Krygier, 1970; Armour et al., 1991; Fleischner, 1994; Moore et al., 2005). Land uses that modify stream channel structure and bank stability can also alter the mechanisms of heat transfer within the stream, typically increasing daily maximum temperatures (Poole and Berman, 2001). Stream temperatures are projected to increase with climate-change due to elevated air temperature and changes in precipitation patterns (Eaton and Scheller, 1996; Mohseni et al., 2003; IPCC, 2007; Battin et al., 2007; van Vliet et al., 2013).

Thermal modeling of current and future climate stream thermal regimes is a central area of research to help guide management actions to create and maintain resilient ecological communities. General circulation models (GCMs) have been criticized as too coarse for watershed applications (Solomon et al., 2007). Therefore modeling techniques that link GCM predictions to watershed and reach scales can provide insight into individual stream's vulnerability to climate-change (Hill et al., 2014) and to provide management tools for fish habitat protection (Caissie, 2006). By modeling climate and restoration scenarios, land managers can be more informed about not only the magnitude of expected warming but also the magnitude of warming that might be offset by management actions (Hannah et al., 2008; Seavy et al., 2009; Roth et al., 2010).

Heat Source modeling (Oregon Department of Environmental Quality, ODEQ, 2012, V7.0) was used to investigate the potential thermal benefits of reforesting riparian areas along a reach of the North Fork Salmon River, California, USA that has little vegetation due to legacy land management practices. The model was calibrated with field data collected in July 2012. Climate warming was simulated in multiple scenarios with uniform increases in mean annual air temperatures and reductions in flow. Each warming scenario was then repeated with partial and full riparian reforestation. Warming between the scenarios was then compared to quantify the relative thermal buffering from reforestation.

2. Methods

2.1. Site description

The Salmon River (often referred to as the "Cal-Salmon") is the second largest tributary of the Klamath River in northern California, USA. The Salmon flows east to west and consists of two major forks, North and South, joining at Forks of the Salmon, CA, USA. The entire watershed drains an area of 1945 km^2 with average annual discharge of 1.5 trillion cubic meters (1.2 million acre-ft.) (Elder et al., 2002). The Salmon River enters the Klamath River upstream of the Trinity River sub-basin. The bulk of the Salmon River's precipitation falls between November and May and varies between 203 cm (80 in.) in the headwaters to less than 100 cm (40 in) at the South Fork (Elder et al., 2002). Elevation ranges from 2609 m in the Trinity Alps to 139 m at its mouth. The Salmon River basin is within a tectonically active north-striking fault zone. It is primarily composed of uplifted mafic igneous and oceanic sedimentary deposits (Ando et al., 1983).

The Salmon River basin has a rich cultural heritage. It is part of the ancestral territories of Karuk, Shasta, and Konomihu first nations. Currently, the Klamath National Forest encompasses 90 % of the Salmon River. The Klamath Basin as a whole has experienced widespread anthropogenic stress, primarily from logging, stream-flow diversion, gravel mining, and hydraulic gold mining (National Research Council, 2004). Klamath tributaries were degraded by human activity resulting in lack of stream cover, sedimentation, and absence of large woody debris (LWD) (National Research Council, 2004; National Marine Fisheries Service, 2012). The Salmon River is listed as thermally impaired under California's List of §303(d) Impaired Water Bodies, with mainstem temperature commonly exceeding salmonid temperature thresholds (CA Environmental Protection Agency, 2002). Juvenile salmonids that over-summer in fresh water, including the United States' federally listed coho salmon (*Oncorhynchus kisutch*) are the most at risk to adverse temperatures (Federal Register, 1997). We conducted our study in July to target elevated summer stream temperatures and investigate reforestation as a potential thermal restoration strategy.

The study site consists of a one-kilometer reach of the North Fork Salmon River (41.316528°N, 123.169097°W). It is located one kilometer upstream of Little North Fork Creek confluence, the last major thermal refuge for up-migrating adult salmonids. The reach was broken into ten habitat units corresponding to runs, riffles, and pools as determined by generalized slope/velocity breaks (USDA Forest Service Region 6 Stream Habitat Inventory Level II Protocol, 2006). The study took place over a two week period in July 2012 and the simulation period was five days.

2.2. Field measurements

Heat Source includes multiple modules that simulate open channel hydraulics and flow routing, stream heat transfers, effective shade (topographic and vegetation) and the resulting stream temperature (Boyd and Kasper, 2003). Modeling required a variety of field measurements including meteorology, mainstem discharge, channel cross-sections, and stream temperature at the upstream boundary. Three eKO Pro Series remote weather stations (Envco Environmental Equipment Suppliers, South Pacific) were deployed over the study period. Each station was equipped with an eS2000 eKO Weather Sensor which measured solar radiation, wind speed and direction, air temperature, humidity, barometric pressure, and precipitation, the latter with a tip-bucket rain gauge. The velocity-area procedure was used to measure stream discharge at the upstream end of the study reach (Environmental Protection Agency, 2006). Discharge and depth were measured at 15