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# Phytoremediation of mining contaminated soil and groundwater by hemp (Cannabis sativa L.) and locally adapted native plants

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# Phytoremediation of mining contaminated soil and groundwater by hemp (*Cannabis sativa* L.) and locally adapted native plants

by
Nathan Carpenter

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**ABSTRACT**

Phytoremediation is an environmentally friendly and cost-effective method of using plants to remediate soils and groundwater by extracting and accumulating contaminants in their tissues. Using locally adapted native plants is preferable to non-native species due to native species being accustomed to the environmental conditions allowing for increased plant growth and fitness. It is typical to use hyperaccumulator plant species since they will grow in soils with very high concentrations of metals and metalloids and show efficient ability to recover (phytoextraction potential) and accumulate (bioconcentration factor) the contaminants in its tissues.

This study focuses on using thirteen locally adapted native plant species and two non-native species to remediate soil and a shallow alluvial aquifer contaminated by historic mining practices in Butte, MT. A controlled greenhouse experiment using soil and groundwater from the North Side Tailings in the Butte Priority Soils Operable Unit was performed to test what plant species can tolerate the metal(loid)s present. Each species phytoextraction potential (PE%) and bioconcentration factor (BCF) was compared to a known hyperaccumulator *Cannabis sativa*, which shows the best metal(loid) tolerance, PE%, and BCF. One native species, *Artemisia ludoviciana,* showed similar tolerance and ability to accumulate and recover Cu, Mn, and Zn to *Cannabis sativa*, but its total recovery was 1-19 times worse. Whereas comparing the other test species showed a significantly different and worse ability tolerate, accumulate, and recover the contaminants. Future research should be done to investigate the plants ability to accumulate and recover contaminants in its root system and compare the greenhouse experiment to a field study.

Since hemp fiber is widely used in industrial manufacturing, further research to understand how hemp fiber quality is impacted when used concurrently for remediation and industrial purposes is important.

Keywords: phytoextraction potential, bioconcentration factor, trace metals, greenhouse experiment, hyperaccumulator, Butte, Montana

## INTRODUCTION

Historic mining practices in Butte, MT have left behind mine waste highly concentrated in arsenic (As), cadmium (Cd), copper (Cu), manganese (Mn), and zinc (Zn) (Tucci & Icopini, 2012). The Parrot Tailings, North Side Tailings, and Diggings East Tailings are the most notable; they have been left untouched since mining ceased and are a significant source of soil and groundwater contamination in the area (Tucci & Icopini, 2012). This project will focus on the Northside Tailings and Diggings East Tailings located around Upper Silver Bow Creek (USBC) in the Butte Priority Soils Operable Unit technical impractibility zone (BPSOU). Groundwater wells in this area have static water levels ranging between 1 and 3.5 meters below surface with high contaminant concentrations. Recreational parks are planned to remediate and restore the landscape in USBC. All groundwater saturated soil will be left in place, and groundwater monitoring and management is planned to keep surface water and Silver Bow Creek contaminant-free (EPA, 2006).

Phytoremediation is an environmentally friendly and cost-effective method of remediating contaminated soils and groundwater that typically implements the use of mycorrhizae. Mycorrhizal fungi form a symbiotic, mutualistic relationship with plants that help establish an ecosystem, improve plant diversity, and increase plant productivity (Quoreshi, 2008). Locally adapted native plant species and mycorrhizae are accustomed to the environmental conditions, and local mycorrhizae will improve plant growth and fitness (Crooks, 2002; Brooks et al., 2004; Charles & Dukes, 2008; Funk et al., 2008; Rúa et al., 2016). Native plants have shown an equal or superior growth and fitness when grown in a system with non-natives (Daehler, 2003).

Traditionally industrial hemp *(Cannabis sativa*) had multiple uses, most importantly it has been a source of fiber and hemp seed oil. Today it is becoming popular among farmers in several states of the US, including Montana, as a multi-purpose agricultural crop and an ideal alternative for organic farming. However, the plant's alternative uses stretch far beyond agriculture. Hemp is a hyperaccumulator meaning that it can grow in soil with very high concentrations of metals and metalloids and concentrates the contaminants in its tissues (Pal & Carpenter, 2020).

In this study, I investigated via a greenhouse experiment which native plant species can withstand the contaminant concentrations found in the soil and groundwater from the Diggings North area, and their respective metal recovery and accumulation potential, to understand which species could be efficient in remediation purposes. In addition, *Cannabis sativa* was used as a non-native test species. Further, the author compared the accuracy of pXRF vs. acid digestion followed by ICP-OES as a method to quantify contaminant concentrations in the plants.

## METHODS

### Soil and Groundwater Collection

Contaminated soil and groundwater for this project were collected in the spring of 2019 in the Butte Priority Soils Operable Unit along Upper Silver Bow Creek (Figure 1). The soil was homogenized, and analyzed for As, Cu, Fe, Mn, Pb, and Zn by acid digestions and analysis via inductively coupled optical emission spectrometry (ICP-OES) at the Montana Bureau of Mines and Geology Analytical Laboratory.

Groundwater was collected from well GS-32S with three 55-gallon drums with a Double Stage Geosquirt 12V DC Purge Pump. Water was stored at room temperature and purged

with nitrogen gas for 1.5 hours a week. Groundwater chemistry and plant growth were monitored weekly.

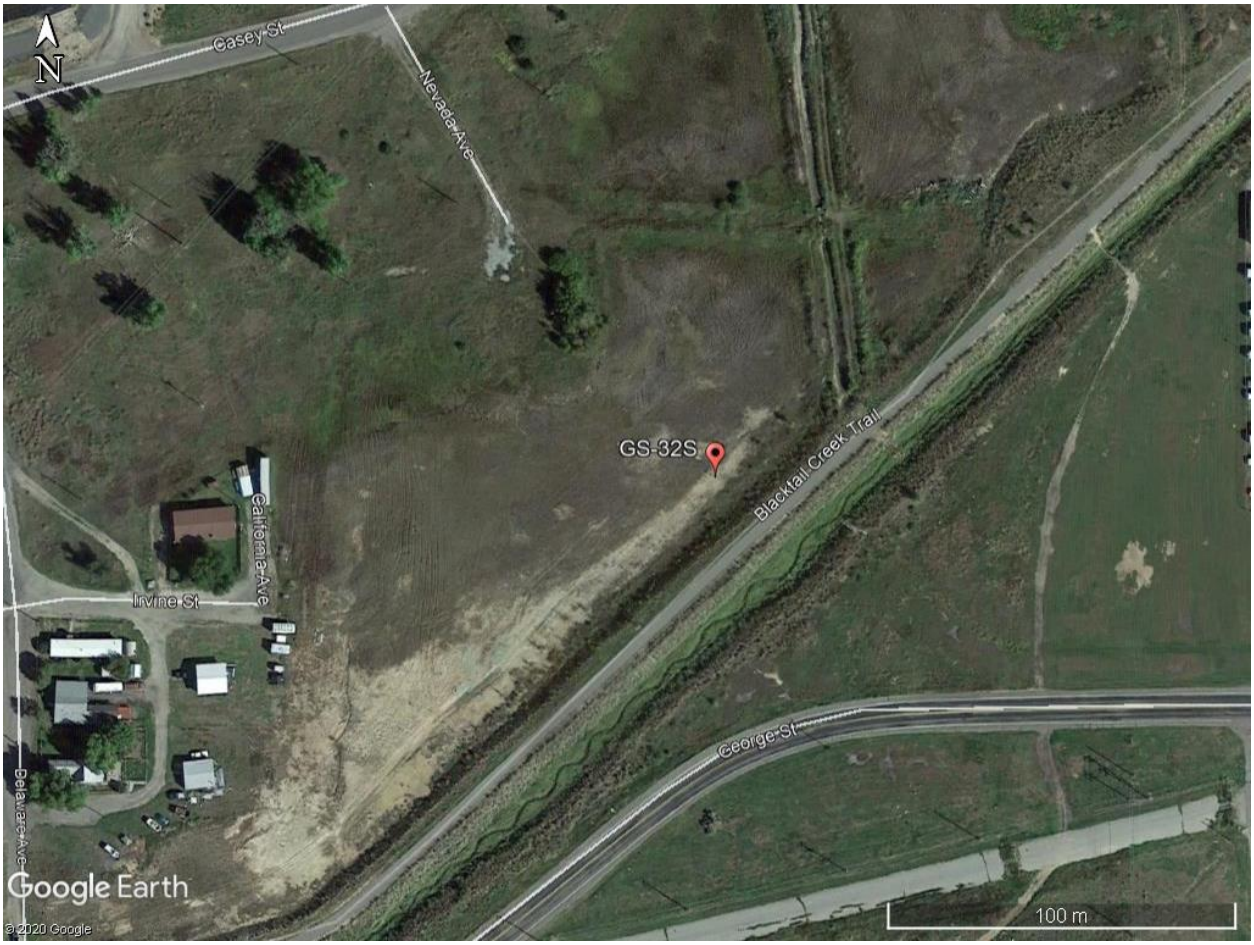


Figure 1. Location of soil and groundwater collection in the Butte Priority Soils Operable Unit. Soil was collected adjacent to the GS-32S groundwater well in Butte, MT.

**Greenhouse Experiment**

The greenhouse portion of this experiment was completed in two stages. The first stage included growing hemp (*Cannabis sativa*) and fourteen native plant species in contaminated soil. The native species were the following: balsam poplar (*Populus balsamifera*), quaking aspen (*Populus tremuloides*), sandbar willow (*Salix exigua*), bluebunch wheatgrass (*Pseudoroegnaria spicata*), shrubby cinquefoil (*Dasiphora fruticosa*), white sagebrush (*Artemisia ludoviciana*), basin wildrye (*Leymus cinereus*),

rubber rabbitbrush (*Ericameria nausesa*), big sagebrush (*Artemisia tridentata*), giant goldenrod (*Solidago gigantea*), common sunflower (*Helianthus annuus*), tufted hairgrass (*Deschampsia caespitosa*), Holbøll's rockcress (*Arabis holbolea*), and silky lupine (*Lupinus sericeus*). Seeds were germinated in a sterile petri dish with filter paper. Deepots D40L 656 mL growing pots were filled with soil collected from the study area, three cotton balls placed in the bottom, and half of the pots getting ½ inch inoculated layer of local mycorrhizae once the pot was ¾ full; mycorrhizae inoculum was collected from the West Side soils in Butte, MT (46°00'43.49" N, 112°34'14.40" W). Preparation of the pots consisted of washing with soap, a bleach soak, and then sterilization with 70% ethanol under a UV light.

Photo 1. Phytoremediation experiment. Photo credit: Robert Pal

The second stage included the same species as stage one, except for the balsam poplar and sandbar willow live cuttings, and shrubby cinquefoil were replaced with non-native wheat (*Triticum aestivum*), blanketflower (*Gaillardia aristat*a), and hairy goldenaster (*Heterotheca villosa*). In this setting seeds were directly placed in the growing pots. Five

seeds were germinated in the pots and thinned down to one individual as germination occurred. Ray Leach Cone-tainers SC10 164 mL were used and filled with a soil mixture of 50% contaminated and 50% potting soil with a ¼ inch inoculated layer of local mycorrhizae once the pot was ¾ full. All plants were monitored weekly with growth measurements. One gram of Osmocote 19-6-12 fertilizer and inorganic phosphate were added to each pot. Inorganic phosphate will induce plants to accept the mycorrhizae since plants cannot uptake inorganic phosphate on their own. Initial watering for all plants was done by an overhead sprinkler system for five, three-minute cycles daily until plants were large enough for the implementation of groundwater (Photo 1).


Figure 2. Treatment groups for the greenhouse experiment. No mycorrhizae indicate there will not be inoculation of mycorrhizae.

Each treatment group received weekly watering with either tap or contaminated groundwater, and either inoculation or no inoculation with mycorrhizae (Figure 2). Once watering with groundwater was implemented, all plants were in bins filled with either tap or groundwater, and they soaked for 1 hour once a week (Photo 2). Greenhouse temperature was kept at roughly 21°C during the day and at 18°C during the nighttime.

Plants were harvested after 16 weeks of growing. Plant samples were washed in tap water, roots and aboveground biomass length was measured. Afterwards plant samples were dried at 60°C for 48 hours and their above and belowground biomass was weighed separately.

Photo 2. Groundwater implementation to the greenhouse experiment.

**Acid Digestion**

For metals and metalloid analysis soil and plant matter samples were weighed out to a dry weight of 0.5 g and divided into roots and shoot/leaf matter. Samples were digested in 15 mL trace metal cleaned digestion vessels with 3 mL of Fisher chemical trace metal nitric acid at 120°C for 4 hours. Once vessels cooled, 1 mL of 30% J.T. Baker™ hydrogen peroxide was added at 70°C for 30 minutes. 15 mL of Q-water was added to each vessel and filtered through Whatman No. 40 0.2 µm paper into a trace metal clean secondary container. Digested samples were diluted to 30 mL with 1% nitric acid. ICP-OES data were corrected for dilutions to represent the mg of metal per kg of plant digested (e.g. converting Zn mg $L^{-1}$ to mg $kg^{-1}$) (Eq. 1):

$$mg\ Zn\ kg\ of\ plant^{-1} = \frac{1000 * Plant\ Zn\ OES\ concentration\ (mg\ L^{-1})}{mass\ of\ plant\ digested\ (g) * final\ digestion\ volume\ (L)} \quad \text{(Eq. 1)}$$

**Groundwater Chemistry**

Water samples collected for dissolved chemistry analysis were stored in 30 mL trace metal (TM) cleaned high density polyethylene (HDPE) Nalgene bottles. Samples were filtered across 25mm, 1.2 and 0.8/0.2 µm polyethersulfone syringe filters using a 1 L HDPE Nalgene bottle, 140 mL polypropylene syringe, polycarbonate stop cock, and Tygon tubing all trace-metal cleaned. 30 mL bottles used for ICP-MS were pre-acidified with 300 µL trace metal grade concentrated nitric acid ($HNO_3$), and ICP-OES samples were preacidifed with 100 µL extra pure, ACROS Organics™ methanesulfonic acid (MSA) Michalski et al., 2011; Oliveira et al., 2010). pH for each sample was measured with a WTW pH 3110 meter with an error of 0.01 and calibrated daily with pH 2, 4, and 7 buffers. Conductivity (µS $cm^{-1}$) was measured with a YSI 30 meter with a conductivity error of 0.5%. Dissolved oxygen (DO) was measured with a PreSens Fibox 4 Trace meter that has a detection limit of 0.94 µmol $kg^{-1}$ and an error of 0.4% (Robertson, 2019).

**X-ray Fluorescence measurements**

Four plant species and 10 replications were picked for method comparison analysis, which are: *Cannabis sativa, Artemisia ludoviciana, Triticum aestivum,* and *Pseudoroegnaria spicata* (Photo 3). Species were chosen depending on how well they grew in the contaminated soil matrix, how they reacted to the introduction of groundwater, and how many replicates survived the greenhouse experiment. Pulverized soil samples and ground plant samples were placed into specialized sample cups designed for pXRF analysis, covered with a Mylar film, and labeled. Soil metals analyses were carried out with a

Thermo Scientific Niton XL3t GOLDD++ model analyzer in “Test-all Geo” mode. The prepared sample cups were placed into the pXRF test stand and tested by the remotely operated pXRF for 40 seconds each: 20 seconds in the Main Menu and 10 seconds for Light and Low elements. A background material tested was aluminum foil.

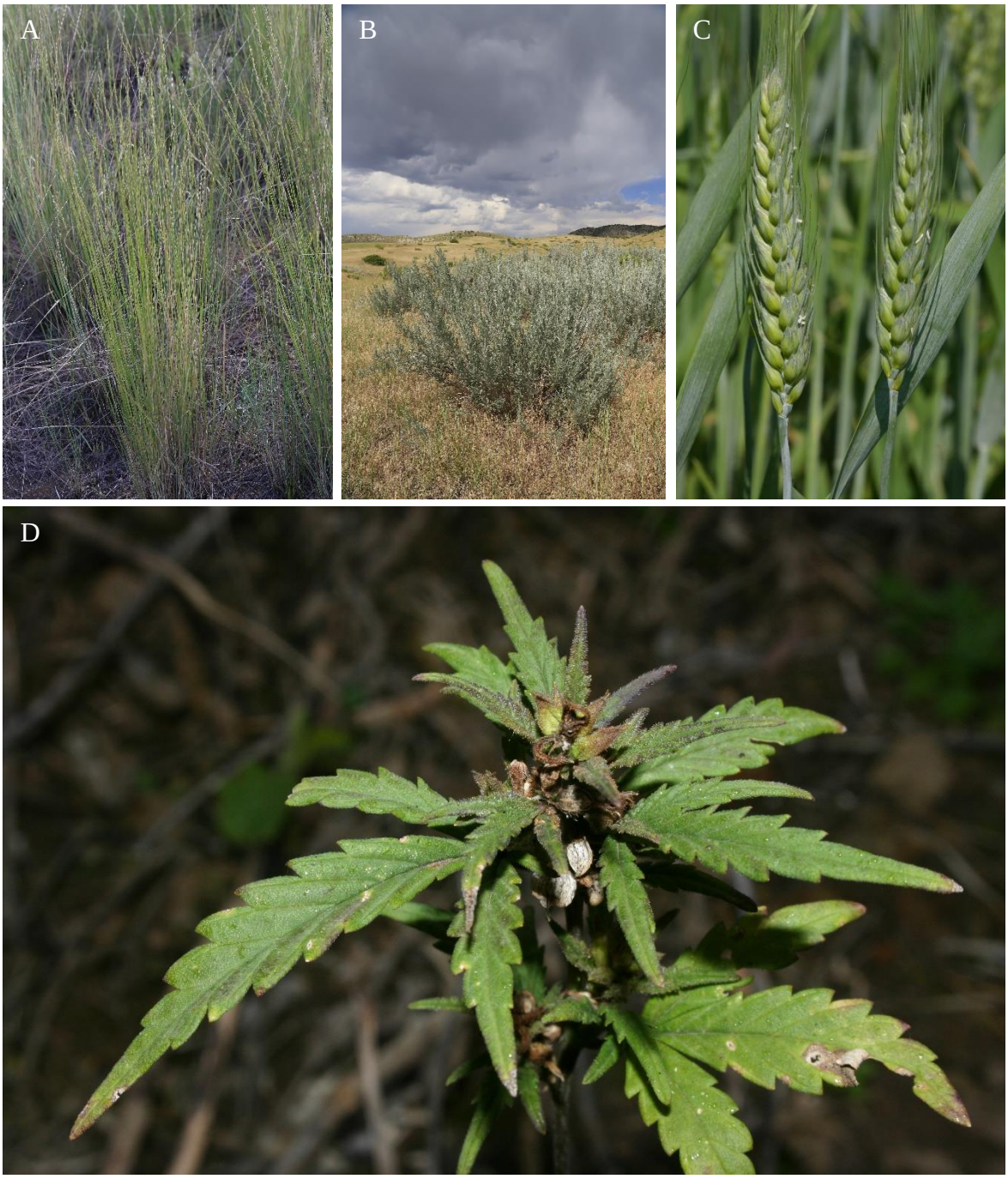


Photo 3. Plant species chosen for analysis via pXRF and ICP-OES. A: *Pseudoroegnaria spicata*, B: *Artemisia ludoviciana,* C: *Triticum aestivum,* D: *Cannabis sativa*. Photo Credit: Robert Pal.

**Method Comparison Analysis**

To test the accuracy of the pXRF, the results were compared to ICP-OES results via the *Method Comparison Regression* (mcr) package in RStudio (Manuilova 2014). The Deming method was used because it quantifies the relationship between two measurement methods; it addresses regression errors in both variables (x- and y- axis) without repeated measurements unlike the simple linear regression model, where the explanatory variable is assumed to be measured without error.

To determine if the datasets are statistically similar, the US EPA standards were used to establish data quality. $R^2$ values greater than 0.85 meet the "definitive" quality level, and $r^2$ between 0.70 and 1.0 meets the "quantitative" quality level, and less than 0.70 meets the "qualitative" quality level (US EPA 1998).

**Phytoextraction Efficiency and Bioconcentration Factor**

Phytoextraction efficiency (PE%) (Eq. 2) looks at the total recovery of metals that plants extract from soil (Yang et al., 2017). The mass of soil in each pot was 217.5 g, which was calculated from the volume of the growing pots (164 mL) multiplied by the density of the soil; the calculated mass was divided by two since the soil matrix consisted of 50% potting soil. The density of the soil from the study area was determined by Tucci (2014), and the alluvial sand has a density of 2655 kg $m^{-3}$.

$$PE\ (\%) = \frac{C_{metal\ concentration\ in\ plant}\ (mg\ kg^{-1}) \times W_{plant\ dry\ weight}\ (g)}{C_{metal\ concentration\ in\ soil}\ (mg\ kg^{-1}) \times\ (217.5\ g\ )} \times 100\% \qquad \text{(Eq. 2)}$$

It is typical to implement bioconcentration factors (BCF) (Eq. 3) when looking at the phytoextraction efficiency of species. BCF looks at the plants ability to accumulate from

the contaminated substrate (Wu et al., 2011). When plants have a bioconcentration factor of less than 1 it is assumed that this plant is not feasible for phytoextraction; however, it has been demonstrated that some species when grown on contaminated soils show great phytoextraction potential with bioconcentration factors less than 0.2 (McGrath & Zhao, 2003).

$$BCF = \frac{C_{concentration\ in\ plants}\ (mg\ kg^{-1})}{C_{concentration\ in\ soil}\ (mg\ kg^{-1})} \quad \text{(Eq. 3)}$$

To compare PE% and BCF between species to understand "how many times greater" each species was to each other, the average of *Cannabis sativa* was divided by the average of each species. *Cannabis sativa* was chosen due to it being a hyperaccumulator and the only non-native test species.

**Plant Species Metal(loid) Tolerance**

A Kruskal-Wallis H test was used to understand how the tolerance to each contaminant compares between species. This is a rank-based nonparametric test that is used to determine if there is statistical difference between groups and does not assume the data variation is normal. The post-hoc Tukey Test was implemented on each species to determine if any species are statistically different (p-value <0.05). A result of 'Do Not Test' (DNT) occurs for a comparison when no significance difference is found between two means that enclose that comparison, and should be treated as no significant difference even if there appears to be one. For example, if you had four means sorted in order, and found no difference between means 4 vs. 2, then you would not test 4 vs. 3 and 3 vs. 2, but still test 4 vs. 1 and 3 vs. 1.

## RESULTS AND DISCUSSION

### Groundwater and Soil Chemistry

One groundwater well (GS-32S) was sampled for trace elements, major cations and anions; *In situ* pH, conductivity, temperature, and dissolved oxygen were measured in the field. 165-gallons of the groundwater was stored and monitored weekly (Table 1A-D). Dissolved oxygen (DO) measurements were not collected *in situ* for 190924B and 190926B; the values were obtained from the "water isotope" sample vial. DO values increased from 5.77 to 7.09 mg $L^{-1}$ for the vial measurements. Weekly drum measurements show a decreasing DO value ranging from 5.52 to 0.68 mg $L^{-1}$ relative to a decreasing pH.

Table 1A. Groundwater parameters for sampling well and storage. D.O. = dissolved oxygen

| Sample ID | Sample Name | T (°C) | pH | Cond. (uS/cm) | D.O. (mg/L) |
|---|---|---|---|---|---|
| 190924B | GS-32S | 21 | 2.432 | 2649 | 5.77 |
| 190926B | Drum 1 (GS-32S) | 19.9 | 2.868 | 2664 | 7.09 |
| 191003B | Drum 1 (GS-32S) | 20.2 | 2.736 | 2528 | 5.52 |
| 191010B | Drum 1 (GS-32S) | 20.7 | 2.694 | 2465 | 2.47 |
| 191017B | Drum 1 (GS-32S) | 19.7 | 2.665 | 2397 | 0.68 |

Major anions (Table 1B) increased in concentration during groundwater storage except for $SO_4^{-2}$ which decreased from 2777 to 2115 mg $L^{-1}$, and $PO_4^{-3}$ decreased from 0.185 mg $L^{-1}$ to BDL two days after groundwater collection.

Table 1B. Major anions for the groundwater well and storage via IC. Units are in ppm; BDL = below detection limit.

| Sample ID | Sample Name | $F^-$ | $Cl^-$ | $Br^-$ | $SO_4^{-2}$ | $PO_4^{-3}$ | $NO_3^-$ |
|---|---|---|---|---|---|---|---|
| 190924B | GS-32S | 4.85 | 108 | BDL | 2777 | 0.185 | 1.76 |
| 190926B | Drum 1 (GS-32S) | 4.43 | 106 | BDL | 2696 | BDL | 1.92 |
| 191003B | Drum 1 (GS-32S) | 5.54 | 113 | 0.088 | 2196 | BDL | 2.54 |
| 191010B | Drum 1 (GS-32S) | 5.49 | 112 | 0.084 | 2198 | BDL | 2.52 |
| 191017B | Drum 1 (GS-32S) | 5.35 | 112 | 0.086 | 2115 | BDL | 2.48 |

Major cations were relatively stable for the extent of groundwater storage except for: $Ca^{+2}$ where the exhibited behavior shows depletion, $K^{+}$ shows slight enrichment within the first two days and depletion during storage, and both $Na^{+}$ and $Mg^{+2}$ show depletion (Table 1C).

Table 1C. Major cations for the groundwater well and storage via IC. Units are in ppm; BDL = below detection limit.

| Sample ID | Sample Name | $Li^{+}$ | $Na^{+}$ | $K^{+}$ | $Mg^{+2}$ | $Ca^{+2}$ |
|---|---|---|---|---|---|---|
| 190924B | GS-32S | 0.324 | 61.4 | 5.66 | 88.4 | 396 |
| 190926B | Drum 1 (GS-32S) | 0.317 | 61.4 | 6.41 | 85.6 | 380 |
| 191003B | Drum 1 (GS-32S) | 0.322 | 58.7 | 6.38 | 85.1 | 377 |
| 191010B | Drum 1 (GS-32S) | 0.326 | 58.1 | 6.20 | 84.8 | 376 |
| 191017B | Drum 1 (GS-32S) | 0.326 | 58.1 | 6.34 | 85.7 | 379 |

Contaminants of concern were analyzed via ICP-OES since the concentrations were above the upper detection limit for ICP-MS; Arsenic is the only exception and was analyzed via ICP-MS. Throughout the groundwater storage, Mn and Cd did not show depletion or enrichment unlike the depletion of Fe, Cu, Zn, and As observed (Table 1D).

Table 1D. Contaminants of concern concentrations for the groundwater well and storage via ICP-OES in ppm. As was analyzed via ICP-MS and is in ppb. BDL = below detection limit.

| Sample ID | Sample Name | Mn | Fe | Cu | Zn | As | Cd | Pb |
|---|---|---|---|---|---|---|---|---|
| 190924A | Blank | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| 190924B | GS-32S | 20.8 | 122 | 120 | 100 | 793 | 0.475 | BDL |
| 190926B | Drum 1 (GS-32S) | 19.4 | 102 | 110 | 92.6 | 304 | 0.442 | 0.196 |
| 191003B | Drum 1 (GS-32S) | 20.5 | 81.4 | 110 | 80.0 | 105 | 0.424 | 0.210 |
| 191010B | Drum 1 (GS-32S) | 20.4 | 74.1 | 111 | 80.0 | 66.3 | 0.415 | BDL |
| 191017B | Drum 1 (GS-32S) | 20.5 | 73.1 | 112 | 80.8 | 58.6 | 0.422 | 0.192 |

Soil was collected from three distinctive layers (Photo 4) to be analyzed for bulk chemistry with pXRF and prepared for ICP-OES analysis via acid digestions (Table 2).

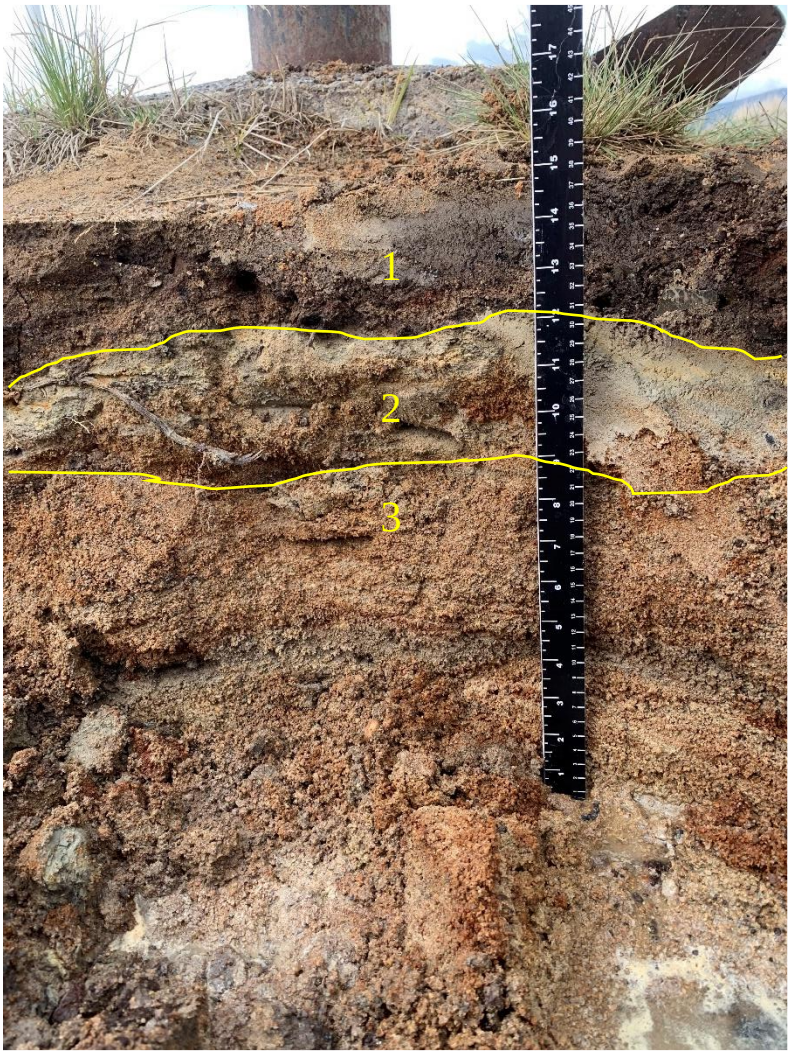


Photo 4. Wall of the soil pit showing the three layers collected for analysis. Yellow lines represent boundary lines between the organic, clay, and alluvial sandy loam.

Table 2. Soil digested mass and contaminants of concern concentrations analyzed via ICP-OES. Units are in ppm.

| Sample Name | Mass (g) | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|---|
| Soil 1 | 0.5127 | 137 | 1281 | 22411 | 351 | 466 | 2417 |
| Soil 2 | 0.5842 | 283 | 293 | 29065 | 196 | 364 | 2783 |
| Soil 3 | 0.421 | 382 | 289 | 27292 | 167 | 324 | 1418 |

**Changing Groundwater Chemistry**

The lowest pH value seen in sample 190924B, which was measured at the time of sampling, is hypothesized to be a result of not purging enough volume of water out of the well. Groundwater concentrations for contaminants of concern did not change with storage except for Fe, Zn, and As which show depletion (Figure 3). pH is the dominating factor for arsenic examined in groundwater; at higher pH it is expected to have higher concentrations

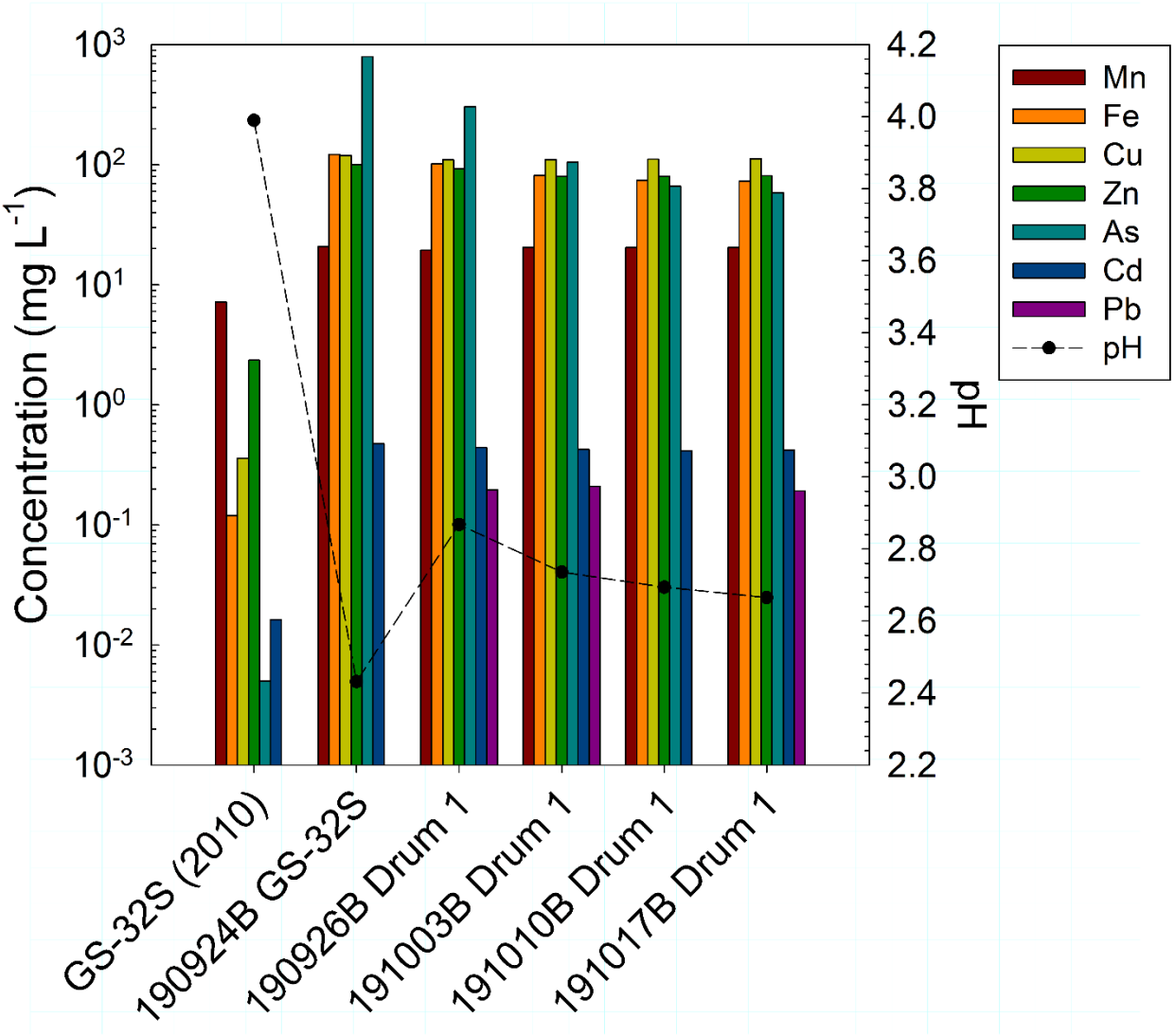


Figure 3. Changing groundwater concentrations. Note two y-axis; sample names year/month/day. Data for GS-32S (2010) was obtained from Montana's GWIC database.

of As (Katsoyiannis & Katsoyiannis 2006).

Ferrous iron concentrations decreased from 0.12 mg $L^{-1}$ to BDL from the precipitation of jarosite ($KFe^{+3}_3(OH)_6(SO_4)_2$) or schwertmannite ($Fe_8O_8(OH)_6(SO_4) \cdot nH_2O$). this precipitation was the likely source of the decrease in $SO_4^{2-}$ concentrations observed (Figure 4). $NH_4^+$ and $S^{-2}$ both have a significant increase two weeks after groundwater collection on 191010B. It is unlikely microbial activity induced the enrichment due to the D.O.

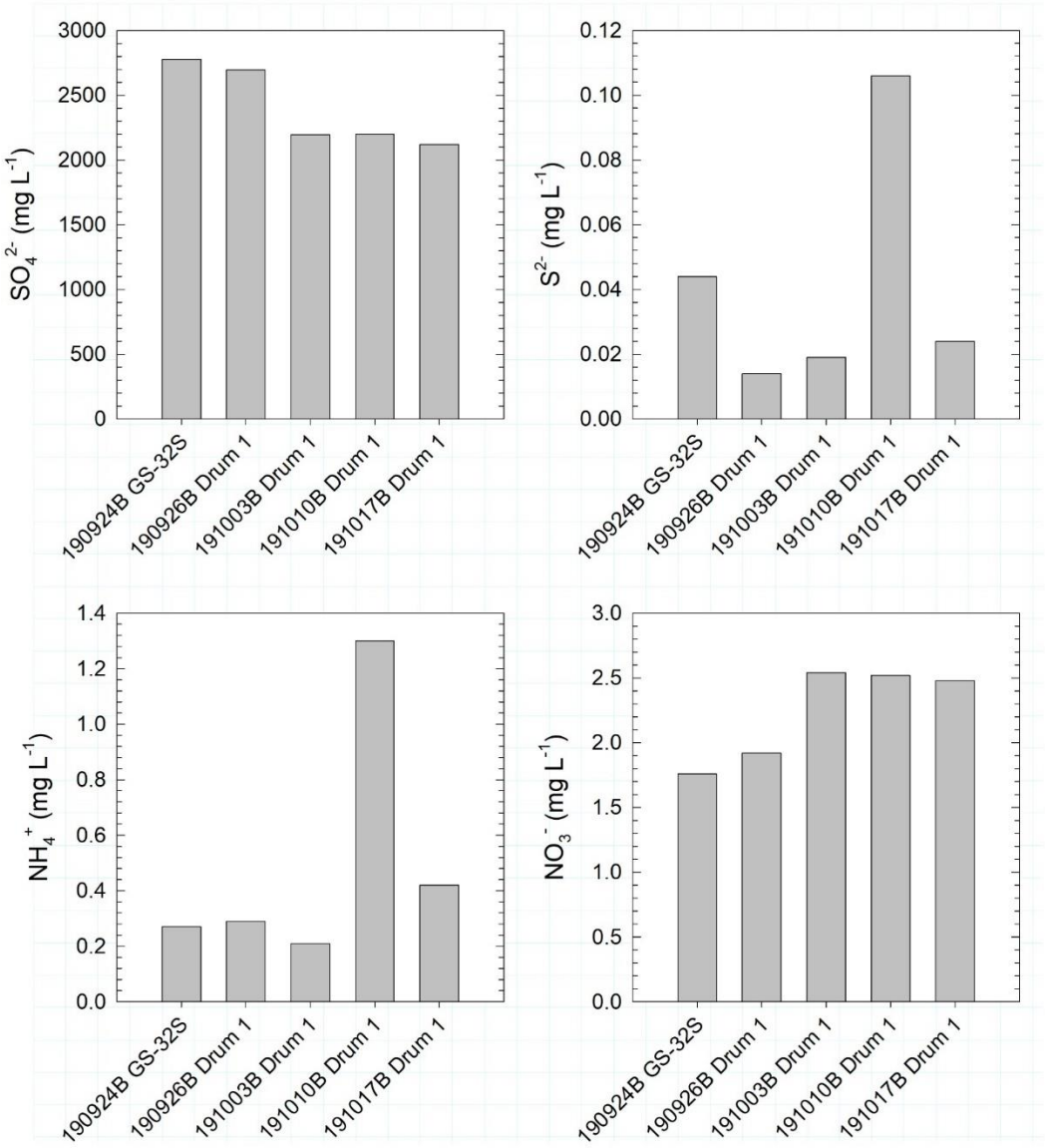


Figure 4. Field spectrophotometry for $NH_4^+$ and $S^{-2}$. $SO_4^{-2}$ and $NO_3^-$ concentrations measured via ICP-OES. Note that each y-axis has a different scale.

concentration being above 0.5 mg $L^{-1}$, and microbial samples for this week are stored at -80 °C.

**Plant Growth**

Weekly growth measurements were made for each plant species. All plant species show no difference between treatment groups during the growing phase. Once plants transitioned to the stationary phase, treatment groups with mycorrhizae are showing increased growth, where non-mycorrhizae groups show either a decrease or increase in growth (Figure 5). Once groundwater was implemented, *Cannabis sativa* and the grasses were either in the stationary phase (Figure 5A and D) or dying (Figure 5C). This is likely a result of the species being at the growing capacity for the growing pots. There was no evidence of the grasses dying or a negative impact on their health (i.e. discoloration, loss of chlorophyll, loss of biomass). *Cannabis sativa* was dying; there was loss of biomass and discoloration in the leaves. *Artemisia ludoviciana* was the only species used for analysis that was still in the growing phase after groundwater implementation (Figure 5B)

Plant growth rates were calculated by taking the natural log of each treatment group's average and determining the slope of the line, which is the growth rate (Figure 6A). The fastest growing plants species are the grasses which include wheat, basin wildrye, and bluebunch wheatgrass; one grass, tufted hairgrass, did not grow as fast. Mycorrhizae appears to have not influenced the growth rate of most of the plant species. The tree species, quaking aspen, and the sub-shrub (between a shrub and a wildflower, steams are woody) species, hairy goldenaster, both have the lowest growth rates besides giant goldenrod which did not germinate. The remaining forbs and shrubs have similar growth rates with variability coming from number of germinated seeds except for rubber rabbitbrush and Holbøll's rockcress, which are slow growers in the soil conditions.

Post groundwater implementation saw the opposite; plants that had a higher growth rate prior resulted in having a lower rate once groundwater was implemented (Figure 6b). Hemp is categorized as a forb, and compared to other forbs, the growth rate was at least double on contaminated soils.

Due to growth rates inhibited by the contamination present, most of the plant species did not have a long enough root system to reach the inoculated layer of mycorrhizal fungi, with the exception for the grass species and *Cannabis sativa*. Post-groundwater introduction (day 56) groups show an increased growth with mycorrhizae, with the groundwater treatment groups having the greatest increase. Two primary sources of this observation are: (1) the death of a replicate or (2) due to the high concentration of $NH_4^+$ and other nutrients in the groundwater. Plant species replicate deaths did occur, but the cause is most likely due to the heavy metal(loid) concentrations in the groundwater and soil. The abundance of nutrients from the groundwater most likely induced increased growth, whether the mycorrhizal fungi was accepted by the host plant. Even though *Artemisia ludoviciana* was still in the growing phase post-groundwater, the growth rate decreased from an average of 0.478 mm $day^{-1}$ to 0.143 mm $day^{-1}$ (Figure 6A-B), and was showing no signs of decreased plant health.

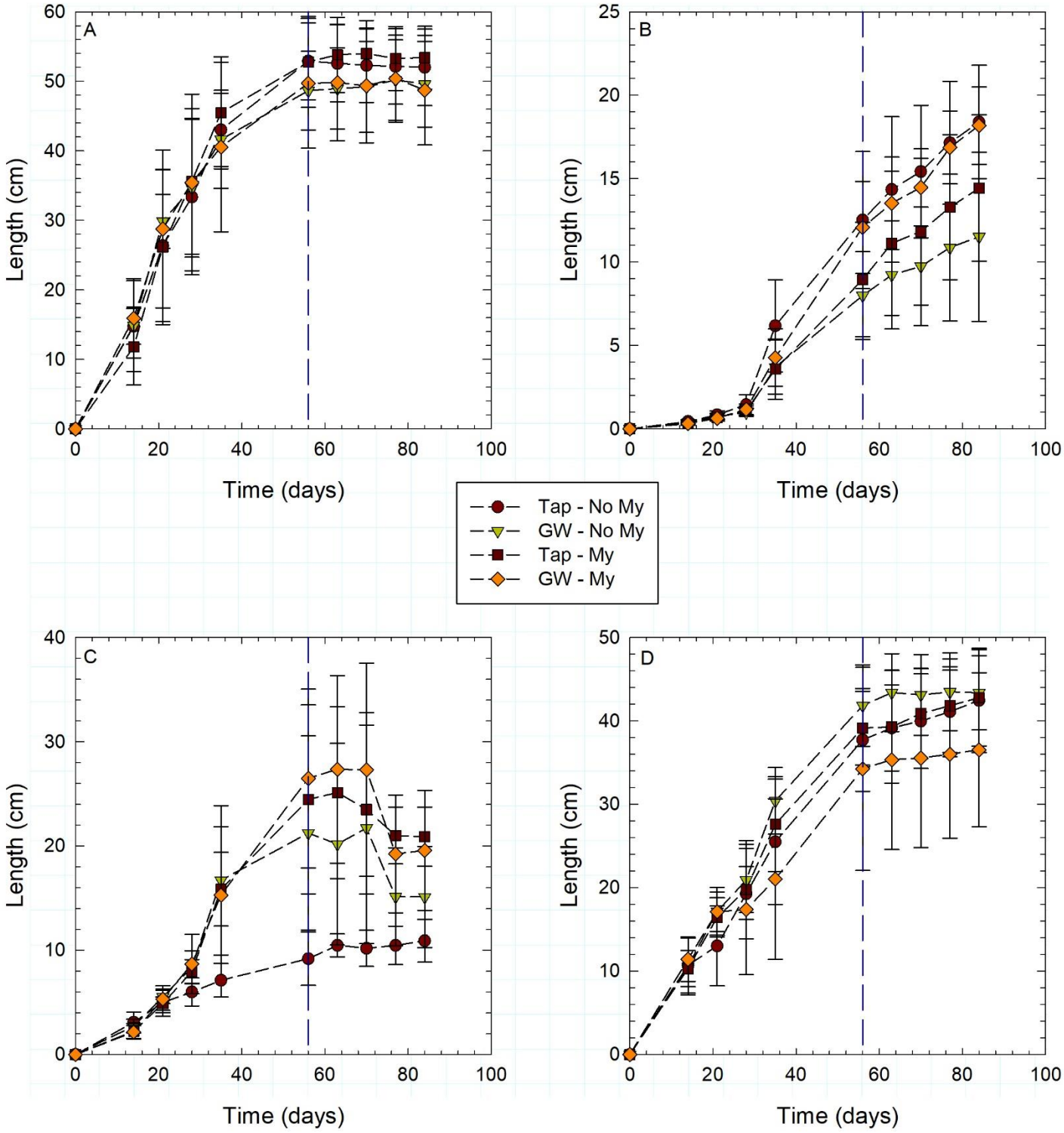


Figure 5. Plant growth during the greenhouse experiment. A: *Triticum aestivum*; B: *Artemisia ludoviciana*; C: *Cannabis sativa*; D: *Pseudoroegnaria spicata*. Each data point represents the average plant length for each treatment group, with error bars representing the standard deviation. Vertical dashed line represents when groundwater was implemented.

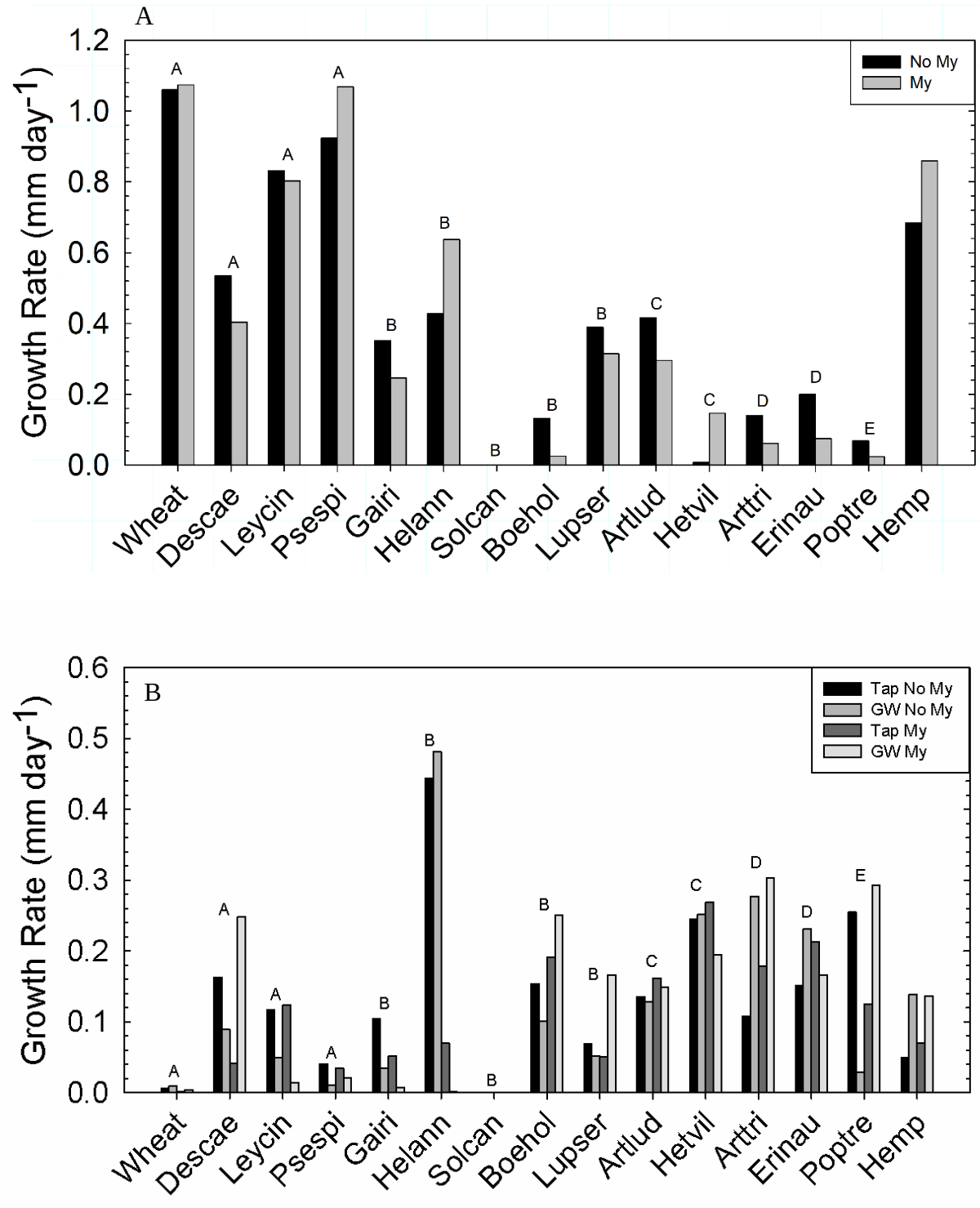


Figure 6. Plant growth rates. A: Pre-GW and B: Post-GW. Plant labels are the abbreviated scientific names of each species with the exception for wheat and hemp. Descae = tufted hairgrass; Gairi = blanketflower; Artlud = white sagebrush; Poptre = quaking aspen; Arttri = big sagebrush; Helann = common sunflower; Boehol = Holbøll's rockcress; Lupser = Pursh's silky lupine; Leycin = basin wildrye; Psespi = bluebunch wheatgrass; Hetvil = hairy goldenaster; Erinau = rubber rabbitbrush. A = Grasses; B = Forbs; C = Sub-shrub; D = shrub; E = tree.

**Plant Species Tolerance to the Present Metal(loids)**

To understand each species ability to withstand and adapt to the higher concentrations of toxic metal(loid)s found, a Kruskal-Wallis H test was conducted between each species and metal(loid) of concern. Among all plants, *Cannabis sativa* and *Artemisia ludoviciana* had the highest tolerance for all metals while *Triticum aestivum* showed moderate tolerance and *Pseudoroegneria spicata* had the lowest.

**Copper**

*Cannabis sativa* compared to *Pseudoroegneria spicata* and *Triticum aestivum* showed a significantly higher level of Cu tolerance at p-value (*P)*=0.016 and *P*=0.028, respectively (Table 3). Comparing *Cannabis sativa* to *Artemisia ludoviciana* and *Artemisia ludoviciana* to *Pseudoroegneria spicata* showed no significant difference at *P*=0.211 and *P*=0.643, respectively. 'Do Not Test' occurred for *Artemisia ludoviciana* to *Triticum aestivum* and *Triticum aestivum* to *Pseudoroegneria spicata*.

Table 3. Kruskal-Wallis H test results on Cu. DNT = Do Not Test

| Comparison | Difference of Means | *P* | P<0.05 |
|---|---|---|---|
| Hemp vs Psespi | 187.9 | 0.016 | Yes |
| Hemp vs Wheat | 174.0 | 0.028 | Yes |
| Hemp vs Artlud | 117.9 | 0.211 | No |
| Artlud vs Psespi | 70.0 | 0.643 | No |
| Artlud vs Wheat | 56.1 | 0.780 | DNT |
| Wheat vs Psespi | 13.9 | 0.995 | DNT |

For copper tolerance, *Cannabis sativa* showed the highest tolerance and *Artemisia ludoviciana* was moderately tolerant (Figure 7). *Artemisia ludoviciana* and *Triticum aestivum* overlapped at low concentrations and showed to be the least tolerable.

**Manganese**

As for Manganese levels in the test plants, *Artemisia ludoviciana* compared to *Triticum aestivum* and *Pseudoroegneria spicata* shows significant difference with $P$=0.007 and $P$=0.010, respectively. *Cannabis sativa* showed no significance between *Artemisia ludoviciana* and *Triticum aestivum* with $P$=0.813 and $P$=0.063, respectively. 'Do Not Test' occurred when comparing *Pseudoroegneria spicata* to *Cannabis sativa* and *Pseudoroegneria spicata* meaning there is no difference (Table 4).

Table 4. Kruskal-Wallis H test results on Mn. DNT = Do Not Test

| Comparison | Difference of Means | *P* | P<0.05 |
|---|---|---|---|
| Artlud vs. Wheat | 296.30 | 0.007 | Yes |
| Artlud vs. Psespi | 286.5 | 0.010 | Yes |
| Artlud vs. Hemp | 75.400 | 0.813 | No |
| Hemp vs. Wheat | 220.90 | 0.063 | No |
| Hemp vs. Psespi | 211.10 | 0.081 | DNT |
| Psespi vs. Wheat | 9.80 | 1.000 | DNT |

For manganese tolerance, *Artemisia ludoviciana* was the most tolerable with *Cannabis sativa;* both overlap within their respective 95% confidence interval. *Triticum aestivum* and *Pseudoroegneria spicata* show the least tolerance and overlap at lower concentrations (Figure 7).

**Iron, Lead, and Zinc**

The differences in median values among plant species were not great enough to deduce whether the variation is due to random sampling variability; therefore, there is not a statistically significant difference between species for Fe, Pb, and Zn with a $P$=0.079, $P$=0.176, and $P$=0.260, respectively.

For iron, species concentrations overlap at all levels meaning that there is not a specific species that shows better tolerance (Figure 7). Fe and Zn are both a required micronutrient for growth and reproduction, so it is expected to see similar tolerance between species. Lead was not detectable in all plant replicates from the ICP-OES.

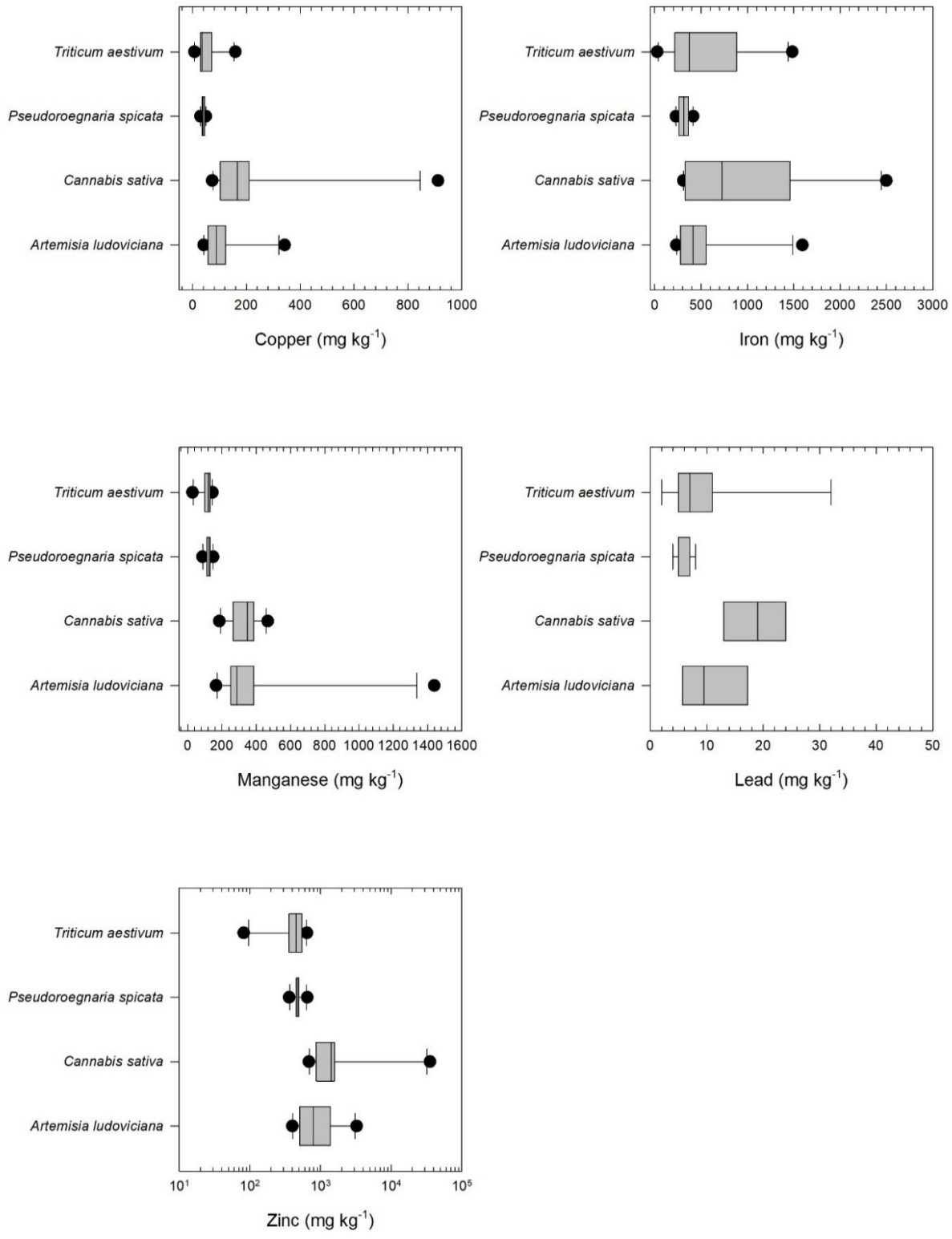


Figure 7. Plant species tolerance to metals of concern. The vertical line within the box represents the difference of means, circles indicate outliers, and error bars represent the 95% confidence interval. Arsenic was excluded due to being below detection limit from ICP-OES.

**Phytoextraction Efficiency and Bioconcentration Factor**

The average phytoextraction efficiency (PE%) and bioconcentration factor (BCF) of *Cannabis sativa* was compared to each test species since *Cannabis sativa* showed the greatest metal(loid) tolerance (Table 5A-B); raw PE% and BCF values are summarized in Appendix A.

The average phytoextraction efficiency (PE%) of hemp was 3-8 times higher compared to the other test plants in the case of copper, 1-4 times higher for Fe, 1-2 times higher for Mn, 4-15 times higher for Pb, and 11-20 times higher in the case of Zn (Table 5A).

Table 5A. Comparing the average PE% of *Cannabis sativa* to each test plant.

| **Species** | **Cu** | **Fe** | **Mn** | **Pb** | **Zn** |
|---|---|---|---|---|---|
| *Artemisia ludoviciana* | 6 | 4 | 1 | 15 | 19 |
| *Pseudoroegneria spicata* | 8 | 4 | 2 | 11 | 20 |
| *Triticum aestivum* | 3 | 1 | 1 | 4 | 11 |

The average bioconcentration factor (BCF) of *Cannabis sativa* was 2-6 times higher compared to the other test species for Cu, 2-3 times higher for Fe, 1-3 times higher for Mn, 4-6 times higher for Pb, and 4-11 times higher in the case of Zn (Table 5B).

Table 5B. Comparing the average BCF of *Cannabis sativa* to each test plant.

| **Species** | **Cu** | **Fe** | **Mn** | **Pb** | **Zn** |
|---|---|---|---|---|---|
| *Artemisia ludoviciana* | 2 | 2 | 1 | 4 | 4 |
| *Pseudoroegneria spicata* | 6 | 3 | 3 | 6 | 10 |
| *Triticum aestivum* | 4 | 2 | 3 | 4 | 11 |

Plant tolerance of Cu differed significantly for *Cannabis sativa* when compared to *Pseudoroegneria spicata* and *Triticum aestivum*, but the PE% between species was 8 and 3 times higher, respectively. *Artemisia ludoviciana* and *Triticum aestivum* show no statistical difference between total recovery, and *Artemisia ludoviciana* shows no significant difference with its ability to accumulate compared to *Cannabis sativa*. *Artemisia ludoviciana* showed similar metal tolerance to *Cannabis sativa* while the PE% was 6 times lower. When looking at the ability to accumulate Cu from the contaminated soil, *Artemisia ludoviciana* and *Triticum aestivum* should, respectively, accumulate 2 and 4 times less than *Cannabis sativa*; however, *Triticum aestivum* exceeded expectations by recovering 3 times less than *Cannabis sativa*, and *Artemisia ludoviciana* underperformed and recovered 6 times less than *Cannabis sativa*. Even though *Cannabis sativa* and *Artemisia ludoviciana* both have the best Cu tolerance, *Triticum aestivum* shows the most similar recovery of Cu from the contaminated soil.

There is no significant difference between Mn and Zn tolerance comparing *Cannabis sativa* to *Artemisia ludoviciana, Pseudoroegneria spicata*, and *Triticum aestivum*. However, *Artemisia ludoviciana* is a sub-shrub and shows significant difference of metal tolerance between the two grasses *Pseudoroegneria spicata* and *Triticum aestivum*, but not *Cannabis sativa,* which is a forb. *Cannabis sativa* can accumulate 3 times more Mn than the grasses, and *Artemisia ludoviciana* is able to accumulate the same as *Cannabis sativa*. *Triticum aestivum* performed better than expected by recovering the same as *Cannabis sativa* and *Atemisia ludoviciana* when it should have recovered 3 times less. When looking at the ability to accumulate Zn, *Cannabis sativa* should accumulate 4 and 11 times more than *Artemisia ludoviciana* and *Triticum aestivum*, respectively. *Triticum aestivum* recovered

what was expected, but *Artemisia ludoviciana* underperformed by recovering 19 times less Zn than *Cannabis sativa*.

*Artemisia ludoviciana* did not transition to a stationary phase meaning that the species was still growing by the end of the greenhouse portion; this might have had an influence on the PE% and BCF. Therefore, if time in the greenhouse was extended for species still growing during groundwater implementation it would be expected to see *Artemisia ludoviciana* with similar or greater metal(loid) tolerance, PE%, and BCF than *Cannabis sativa*, which is a hyperaccumulator.

**Comparing the Outcomes of pXRF and ICP-OES Analyses**

The pXRF overreported all contaminants 1 to 10 times more than the ICP-OES analysis with the exception for a few samples close to 1:1 and 100:1 (Figure 8).

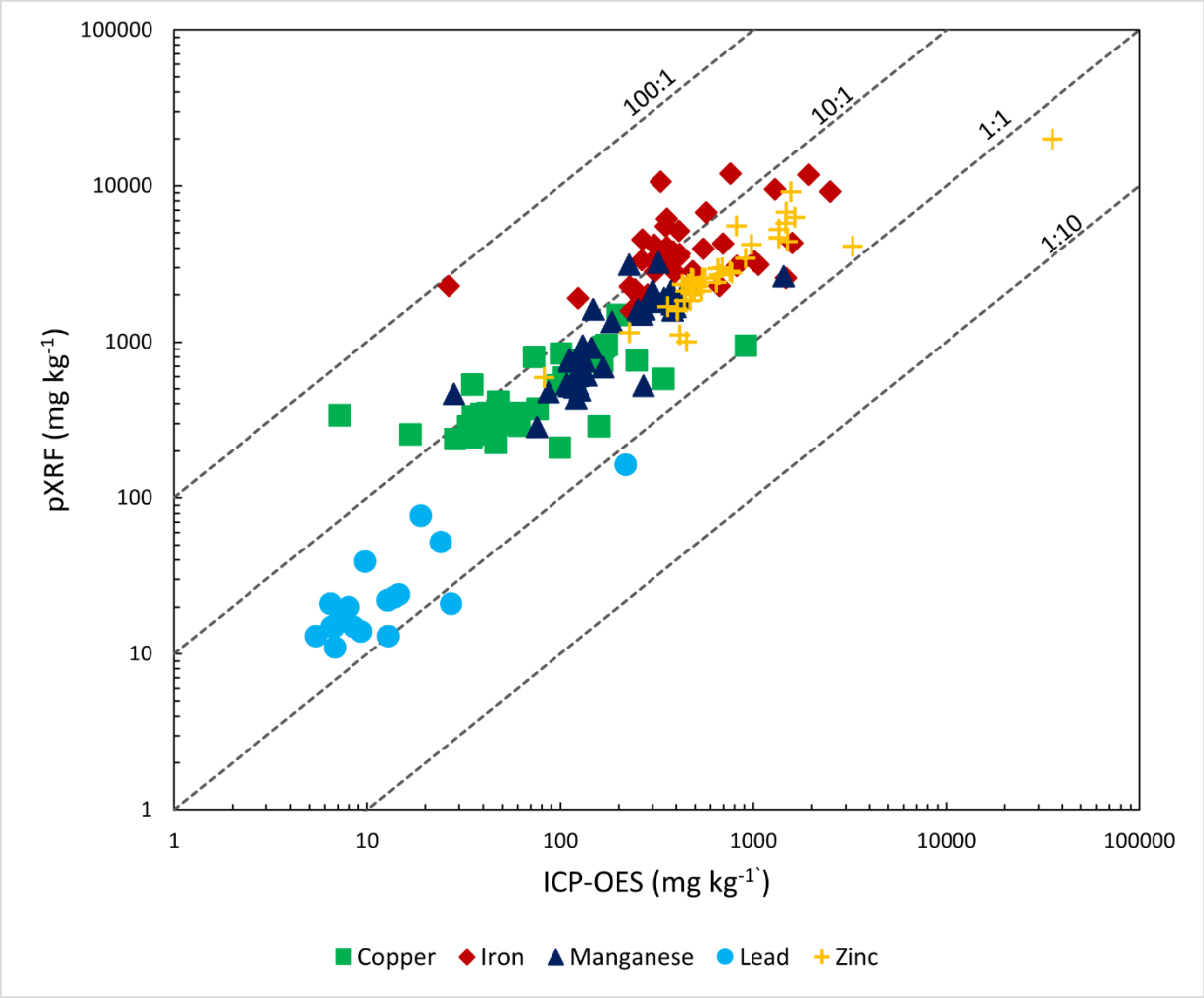


Figure 8. Method comparison of metal concentrations determined by pXRF and by ICP-OES for all plant samples. Dashed lines represent ratios between the two.

Looking at individual species (Figure 9A-D), *Pseudoroegnaria spicata* shows the least variability in precision for concentrations unlike *Artemisia ludoviciana*, *Cannabis sativa*, and *Triticum aestivum*. There was no statistical difference found between treatment groups for each individual species.

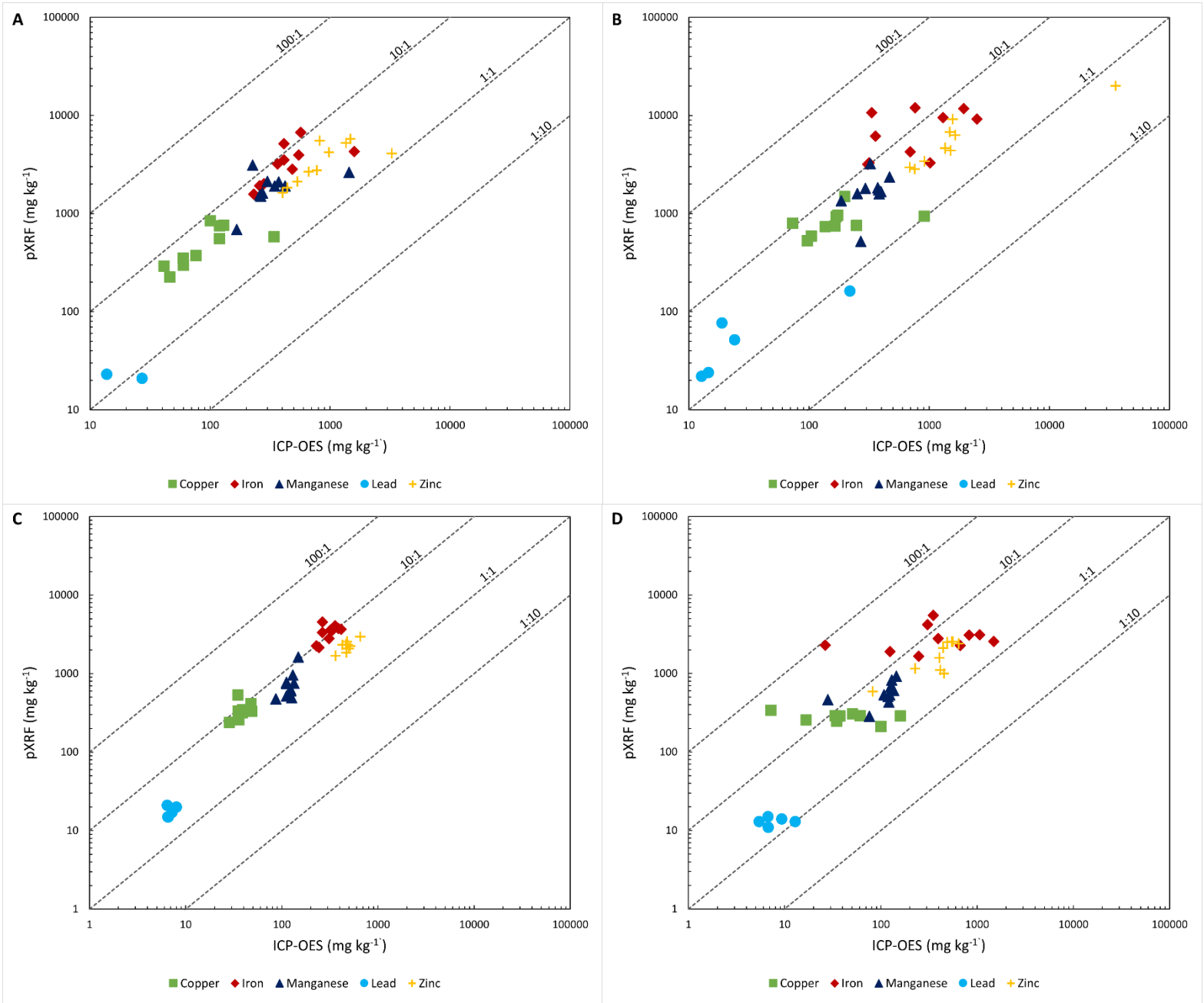


Figure 9. ICP-OES and pXRF concentrations for each plant species. Dashed lines represent ratios between the two. A: *Artemisia ludoviciana*; B: *Cannabis sativa*; C: *Pseudoroegnaria spicata*; D: *Triticum aestivum*

To test the accuracy of the pXRF, the results were compared to ICP-OES results via a Deming regression in the *Method Comparison Regression* (mcr) package in RStudio, and the quality of data was determined by following the US EPA data quality guidelines (Manuilova 2014).

Zn and Pb had $r^2$ values of 0.868 and 0.917 respectively (Figure 10) which meet the US EPA standards of definitive data quality level, and agrees with the findings of Trilling (2018) besides Cu; however the number of observations for the Pb analysis was 19, and each other analysis had 40 with the exception of As. Arsenic, Cu, Mn, and Fe had $r^2$ values of 0.599, 0.521, 0.622, and 0.520, respectively, which is at the "qualitative" data quality level meaning that the datasets are statistically different.

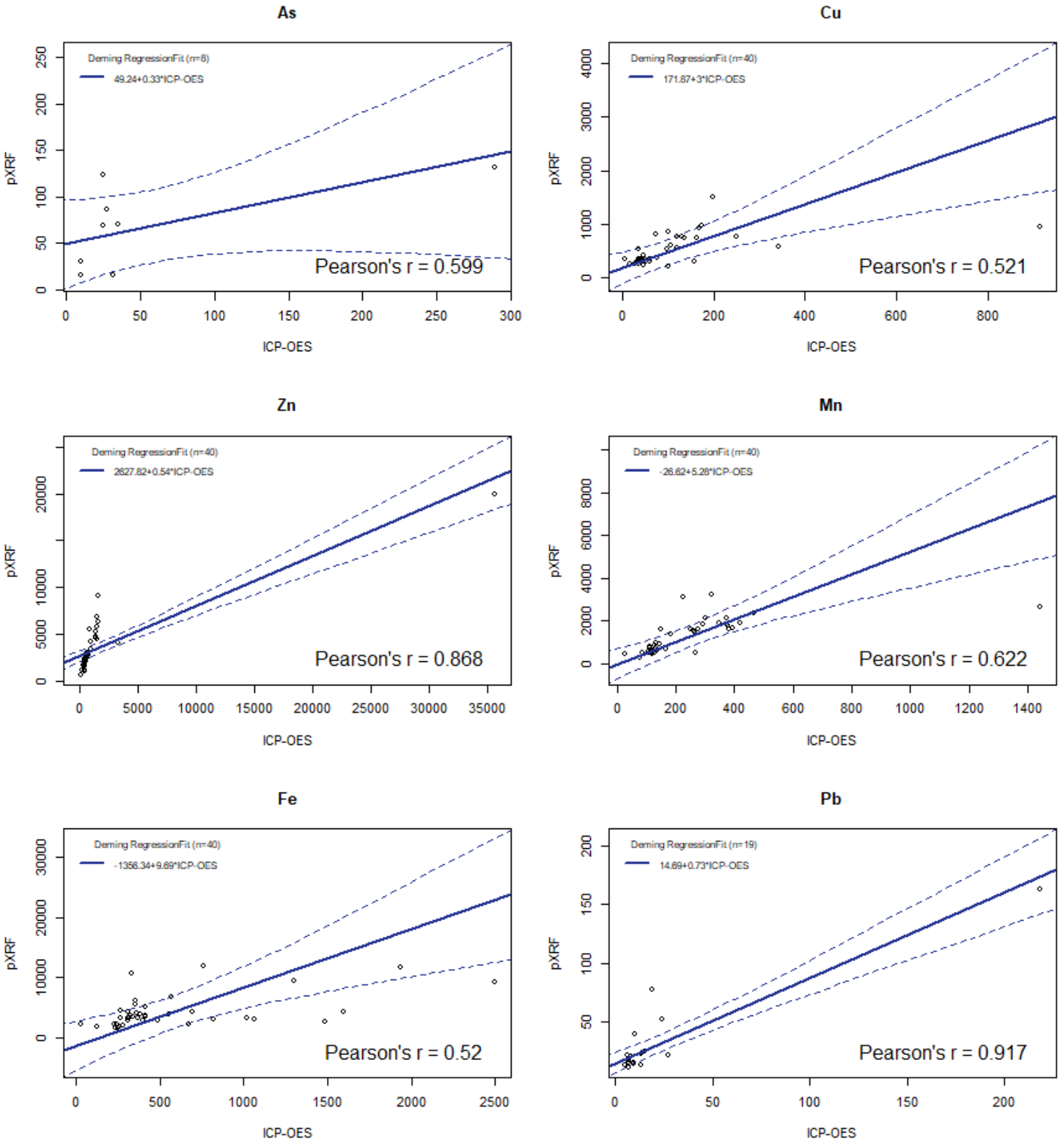


Figure 10. Deming regression analysis of pXRF against ICP-OES analysis. Deming relationship (solid blue line) and confidence intervals (dashed blue line) are shown on each plot; data is in units of mg $kg^{-1}$.

## CONCLUSION

Decades of mining in Butte, MT has left a detrimental impact on the soil and groundwater quality within the community. We have demonstrated that plants will germinate and grow in a soil matrix of 50% contaminated soil and 50% potting soil but will have inhibited health and growth in 100% contaminated soil. The shallow alluvial aquifer will provide an abundance of needed nutrients to the plants. *Cannabis sativa* and *Artemisia ludoviciana* were the most tolerable to the heavy metals and metalloids present and both have great potential for use in remedial purposes. Future research on this topic should re-examine the greenhouse portion and implement the groundwater at the start or extend the length of groundwater treatment to provide the species with more time to extract and accumulate the contaminants, and also compare the results to a field experiment; comparing metal(loid) concentrations found in stems/leaves to the roots would help understand how the contamination is inhibiting the growth of the root system; a metagenomic survey of the soil, groundwater, and samples of the stored groundwater would allow us to understand what ecological interactions are happening on the microbial level. Further research on how the contamination impacted the quality of hemp fiber would be useful because it is important to understand how hemp fiber quality will be influenced when used concurrently for phytoremediation and industrial manufacturing purposes.

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## APPENDIX

Table 3. pXRF data for replicates used in analysis; units are in ppm. BDL = below detection limit

| Sample | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|
| Artlud 9 | 26 | 226 | 2012 | 689 | BDL | 1630 |
| Artlud 12 | 51 | 844 | 5137 | 3123 | 26 | 5546 |
| Artlud 13 | 29 | 581 | 4297 | 2624 | 21 | 4105 |
| Artlud 14 | 32 | 555 | 2840 | 2100 | BDL | 5778 |
| Artlud 15 | 44 | 751 | 6737 | 2130 | 39 | 5240 |
| Artlud 17 | 19 | 763 | 3516 | 1622 | 21 | 4205 |
| Artlud 25 | 37 | 351 | 3955 | 1504 | 23 | 1839 |
| Artlud 28 | 26 | 291 | 3199 | 1550 | 15 | 2680 |
| Artlud 37 | 17 | 373 | 1578 | 1913 | BDL | 2756 |
| Artlud 39 | 24 | 297 | 1920 | 1906 | BDL | 2122 |
| Hemp 2 | 51 | 799 | 10654 | 1586 | 43 | 2833 |
| Hemp 3 | 54 | 528 | 3174 | 1681 | BDL | 3425 |
| Hemp 10 | 69 | 587 | 11738 | 1838 | 24 | 2964 |
| Hemp 16 | 83 | 929 | 6156 | 2361 | 58 | 4620 |
| Hemp 18 | 86 | 958 | 3289 | 3222 | 31 | 4658 |
| Hemp 28 | 132 | 944 | 9168 | 522 | 163 | 19966 |
| Hemp 29 | 124 | 1493 | 11982 | 1349 | 77 | 9134 |
| Hemp 34 | 87 | 744 | 9498 | 1749 | 52 | 4391 |
| Hemp 36 | 165 | 759 | 3284 | 1811 | BDL | 6780 |
| Hemp 39 | 70 | 738 | 4257 | 1603 | 22 | 6303 |
| Psespi 1 | 25 | 240 | 3779 | 752 | 20 | 1676 |
| Psespi 4 | 31 | 256 | 2807 | 520 | BDL | 1833 |
| Psespi 14 | 19 | 349 | 3591 | 771 | 15 | 2089 |
| Psespi 16 | 17 | 335 | 2154 | 488 | BDL | 2078 |
| Psespi 31 | 28 | 317 | 2265 | 604 | BDL | 2327 |
| Psespi 32 | 27 | 345 | 3535 | 476 | 15 | 2327 |
| Psespi 33 | 23 | 332 | 3662 | 629 | BDL | 2940 |
| Psespi 35 | 32 | 532 | 4544 | 1616 | BDL | 2260 |
| Psespi 38 | 20 | 333 | 3329 | 948 | 21 | 2552 |
| Psespi 39 | 23 | 411 | 4058 | 747 | 17 | 2347 |
| Wheat 1 | 15 | 289 | 1664 | 510 | BDL | 1001 |
| Wheat 3 | 19 | 256 | 1901 | 919 | BDL | 1105 |
| Wheat 4 | BDL | 340 | 2282 | 465 | BDL | 591 |
| Wheat 16 | 16 | 304 | 2788 | 607 | BDL | 2549 |
| Wheat 17 | 19 | 291 | 3119 | 433 | 13 | 2118 |
| Wheat 18 | 23 | 286 | 4194 | 537 | 13 | 2515 |
| Wheat 19 | 24 | 288 | 5515 | 676 | 11 | 2551 |
| Wheat 21 | 16 | 211 | 2280 | 536 | 14 | 1151 |
| Wheat 23 | 16 | 246 | 3076 | 285 | 15 | 1588 |
| Wheat 39 | 17 | 288 | 2562 | 825 | BDL | 2407 |

Table 4. Average pXRF for *Artemisia ludoviciana*; units are in ppm. NA = not measured

| Sample | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|
| Artlud 1 | 14 | 94 | 599 | 258 | 16 | 404 |
| Artlud 3 | 10 | 73 | 323 | 103 | NA | 187 |
| Artlud 5 | 9 | 74 | 356 | 145 | NA | 365 |
| Artlud 6 | 12 | 73 | 447 | 170 | 6 | 457 |
| Artlud 7 | 10 | 232 | 522 | 158 | 11 | 450 |
| Artlud 8 | NA | 44 | 712 | NA | 164 | 155 |
| Artlud 9 | 26 | 226 | 2012 | 689 | NA | 1630 |
| Artlud 12 | 51 | 844 | 5137 | 3123 | 26 | 5546 |
| Artlud 13 | 29 | 581 | 4297 | 2624 | 21 | 4105 |
| Artlud 14 | 32 | 555 | 2840 | 2100 | NA | 5778 |
| Artlud 15 | 44 | 751 | 6737 | 2130 | 39 | 5240 |
| Artlud 17 | 19 | 763 | 3516 | 1622 | 21 | 4205 |
| Artlud 19 | 14 | 317 | 1831 | 1692 | NA | 2880 |
| Artlud 20 | 23 | 712 | 3098 | 1112 | NA | 3532 |
| Artlud 22 | 19 | 293 | 2517 | 452 | NA | 1220 |
| Artlud 23 | 17 | 246 | 1841 | 634 | NA | 1510 |
| Artlud 24 | 26 | 313 | 1970 | 641 | NA | 1283 |
| Artlud 25 | 37 | 351 | 3955 | 1504 | 23 | 1839 |
| Artlud 27 | 24 | 230 | 2147 | 615 | 12 | 1268 |
| Artlud 28 | 26 | 291 | 3199 | 1550 | 15 | 2680 |
| Artlud 29 | 19 | 260 | 2219 | 915 | NA | 1582 |
| Artlud 32 | 21 | 346 | 1796 | 1362 | NA | 2824 |
| Artlud 33 | 22 | 475 | 1977 | 1504 | NA | 2399 |
| Artlud 34 | 14 | 270 | 1877 | 1041 | NA | 1640 |
| Artlud 35 | 17 | 313 | 1781 | 772 | NA | 1684 |
| Artlud 37 | 17 | 373 | 1578 | 1913 | NA | 2756 |
| Artlud 39 | 24 | 297 | 1920 | 1906 | NA | 2122 |
| Artlud 40 | 17 | 387 | 2455 | 962 | NA | 2569 |

Table 5. Average pXRF data for *Cannabis sativa*; units are in ppm. NA = not measured

| Sample | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|
| Hemp 2 | 51 | 799 | 10654 | 1586 | 43 | 2833 |
| Hemp 3 | 54 | 528 | 3174 | 1681 | NA | 3425 |
| Hemp 6 | 66 | 369 | 2694 | 2455 | NA | 2344 |
| Hemp 10 | 69 | 587 | 11738 | 1838 | 24 | 2964 |
| Hemp 11 | 57 | 546 | 2577 | 467 | NA | 2719 |
| Hemp 12 | 21 | 441 | 2978 | 1485 | NA | 1651 |
| Hemp 13 | 43 | 702 | 3892 | 1467 | 18 | 3735 |
| Hemp 14 | 36 | 309 | 2853 | 862 | NA | 2517 |
| Hemp 16 | 83 | 929 | 6156 | 2361 | 58 | 4620 |
| Hemp 17 | 65 | 719 | 6614 | 1273 | 59 | 3280 |
| Hemp 18 | 86 | 958 | 3289 | 3222 | 31 | 4658 |
| Hemp 21 | 47 | 565 | 11369 | 1021 | 26 | 2023 |
| Hemp 23 | 47 | 343 | 3141 | 1119 | 29 | 1860 |
| Hemp 25 | 65 | 741 | 4096 | 1114 | 39 | 4252 |
| Hemp 27 | 22 | 309 | 2606 | 1284 | NA | 1804 |
| Hemp 28 | 132 | 944 | 9168 | 522 | 163 | 19966 |
| Hemp 29 | 124 | 1493 | 11982 | 1349 | 77 | 9134 |
| Hemp 30 | 76 | 446 | 6845 | 1103 | 24 | 3125 |
| Hemp 33 | 40 | 604 | 4258 | 1478 | 21 | 4853 |
| Hemp 34 | 87 | 744 | 9498 | 1749 | 52 | 4391 |
| Hemp 35 | 72 | 534 | 2963 | 1548 | NA | 3294 |
| Hemp 36 | 165 | 759 | 3284 | 1811 | NA | 6780 |
| Hemp 37 | 100 | 811 | 8946 | 1343 | 36 | 3225 |
| Hemp 38 | 31 | 393 | 3308 | 1101 | 14 | 1971 |
| Hemp 39 | 70 | 738 | 4257 | 1603 | 22 | 6303 |
| Hemp 2 | 51 | 799 | 10654 | 1586 | 43 | 2833 |
| Hemp 3 | 54 | 528 | 3174 | 1681 | NA | 3425 |
| Hemp 6 | 66 | 369 | 2694 | 2455 | NA | 2344 |

Table 6. Average pXRF data for *Pseudoroegnaria spicata*; units are in ppm. NA = not measured

| Sample | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|
| Psespi 1 | 25 | 240 | 3779 | 3779 | 20 | 1676 |
| Psespi 2 | 15 | 138 | 892 | 892 | 7 | 865 |
| Psespi 3 | 15 | 162 | 1608 | 1608 | NA | 1398 |
| Psespi 4 | 31 | 256 | 2807 | 2807 | NA | 1833 |
| Psespi 6 | 18 | 219 | 2153 | 2153 | NA | 2624 |
| Psespi 8 | 22 | 225 | 2614 | 2614 | NA | 1402 |
| Psespi 10 | 18 | 183 | 2367 | 2367 | NA | 1287 |
| Psespi 14 | 19 | 349 | 3591 | 3591 | 15 | 2089 |
| Psespi 15 | 18 | 308 | 2814 | 2814 | NA | 1993 |
| Psespi 16 | 17 | 335 | 2154 | 2154 | NA | 2078 |
| Psespi 17 | 13 | 249 | 1618 | 1618 | NA | 1613 |
| Psespi 18 | 14 | 311 | 2087 | 2087 | NA | 1998 |
| Psespi 19 | 17 | 372 | 2552 | 2552 | NA | 1955 |
| Psespi 20 | 18 | 347 | 2440 | 2440 | NA | 1788 |
| Psespi 21 | 19 | 207 | 2192 | 2192 | 14 | 1603 |
| Psespi 22 | 19 | 225 | 2256 | 2256 | 13 | 1206 |
| Psespi 23 | 17 | 206 | 2031 | 2031 | NA | 1346 |
| Psespi 24 | 30 | 255 | 2482 | 2482 | NA | 1838 |
| Psespi 27 | 17 | 219 | 2606 | 2606 | NA | 1301 |
| Psespi 28 | 20 | 219 | 2758 | 2758 | 12 | 952 |
| Psespi 29 | 21 | 270 | 2537 | 2537 | NA | 1387 |
| Psespi 31 | 28 | 317 | 2265 | 2265 | NA | 2327 |
| Psespi 32 | 27 | 345 | 3535 | 3535 | 15 | 2327 |
| Psespi 33 | 23 | 332 | 3662 | 3662 | NA | 2940 |
| Psespi 35 | 32 | 532 | 4544 | 4544 | NA | 2260 |
| Psespi 38 | 20 | 333 | 3329 | 3329 | 21 | 2552 |
| Psespi 39 | 23 | 411 | 4058 | 4058 | 17 | 2347 |
| Psespi 40 | 16 | 237 | 2025 | 2025 | NA | 1814 |

Table 7. Table 6. Average pXRF data for *Triticum aestivum*; units are in ppm. NA = not measured

| Sample | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|
| Wheat 1 | 15 | 289 | 1664 | 510 | NA | 1001 |
| Wheat 3 | 19 | 256 | 1901 | 919 | NA | 1105 |
| Wheat 4 | NA | 340 | 2282 | 465 | NA | 591 |
| Wheat 5 | 10 | 123 | 552 | 181 | NA | 690 |
| Wheat 6 | 12 | 102 | 826 | 158 | NA | 999 |
| Wheat 7 | 11 | 191 | 1295 | 568 | NA | 955 |
| Wheat 8 | 12 | 172 | 1195 | 247 | NA | 1339 |
| Wheat 11 | 11 | 217 | 1663 | 546 | NA | 1863 |
| Wheat 12 | 14 | 252 | 2191 | 549 | NA | 1435 |
| Wheat 15 | 13 | 241 | 1396 | 686 | NA | 2872 |
| Wheat 16 | 16 | 304 | 2788 | 607 | NA | 2549 |
| Wheat 17 | 19 | 291 | 3119 | 433 | 13 | 2118 |
| Wheat 18 | 23 | 286 | 4194 | 537 | 13 | 2515 |
| Wheat 19 | 24 | 288 | 5515 | 676 | 11 | 2551 |
| Wheat 21 | 16 | 211 | 2280 | 536 | 14 | 1151 |
| Wheat 23 | 16 | 246 | 3076 | 285 | 15 | 1588 |
| Wheat 24 | 14 | 196 | 2251 | 188 | 15 | 1081 |
| Wheat 25 | 13 | 173 | 1154 | 368 | NA | 1500 |
| Wheat 26 | 16 | 217 | 1473 | 419 | NA | 1746 |
| Wheat 29 | 13 | 180 | 1021 | 377 |  | 1038 |
| Wheat 30 | 11 | 219 | 1469 | 320 |  | 1365 |
| Wheat 31 | 9 | 189 | 985 | 227 |  | 929 |
| Wheat 32 | 15 | 271 | 2014 | 458 |  | 893 |
| Wheat 33 | 10 | 240 | 1754 | 227 |  | 1245 |
| Wheat 34 |  | 134 | 1265 |  |  | 626 |
| Wheat 37 | 21 | 241 | 3353 | 154 | 11 | 1251 |
| Wheat 38 | 14 | 300 | 1980 | 159 |  | 1080 |
| Wheat 39 | 17 | 288 | 2562 | 825 |  | 2407 |

Table 8. Corrected ICP-OES concentrations. Units in mg $kg^{-1}$. Blank cells = not measured

| Sample | Mass (g) | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|---|
| Artlud 9 | 0.2578 | | 46 | 282 | 166 | 6 | 401 |
| Artlud 12 | 0.098 | | 101 | 413 | 227 | | 817 |
| Artlud 13 | 0.0352 | | 342 | 1594 | 1440 | 27 | 3264 |
| Artlud 14 | 0.0611 | | 120 | 485 | 374 | | 1478 |
| Artlud 15 | 0.0791 | | 120 | 569 | 301 | 10 | 1362 |
| Artlud 17 | 0.0322 | | 130 | 412 | 274 | | 978 |
| Artlud 25 | 0.1552 | | 60 | 549 | 265 | 14 | 439 |
| Artlud 28 | 0.1432 | | 41 | 365 | 260 | 9 | 664 |
| Artlud 37 | 0.1788 | | 76 | 232 | 421 | | 773 |
| Artlud 39 | 0.2622 | | 60 | 259 | 346 | 5 | 535 |
| Hemp 2 | 0.0657 | | 73 | 332 | 383 | | 758 |
| Hemp 3 | 0.1695 | | 97 | 308 | 396 | 5 | 913 |
| Hemp 10 | 0.14 | 25 | 105 | 1939 | 373 | 15 | 688 |
| Hemp 16 | 0.0165 | | 168 | 356 | 467 | | 1358 |
| Hemp 18 | 0.0578 | | 173 | 316 | 322 | | 1360 |
| Hemp 28 | 0.4802 | 289 | 912 | 2499 | 269 | 218 | 35610 |
| Hemp 29 | 0.1654 | 25 | 198 | 762 | 185 | 19 | 1565 |
| Hemp 34 | 0.201 | 28 | 164 | 1300 | 379 | 24 | 1507 |
| Hemp 36 | 0.0519 | | 249 | 1017 | 294 | 20 | 1486 |
| Hemp 39 | 0.1392 | 35 | 136 | 694 | 252 | 13 | 1642 |
| Psespi 1 | 0.1578 | | 29 | 386 | 134 | 8 | 361 |
| Psespi 4 | 0.3175 | 10 | 36 | 309 | 111 | 5 | 471 |
| Psespi 14 | 0.1913 | | 42 | 321 | 112 | 7 | 496 |
| Psespi 16 | 0.2604 | | 44 | 243 | 127 | 4 | 474 |
| Psespi 31 | 0.1576 | | 39 | 228 | 124 | 5 | 482 |
| Psespi 32 | 0.1853 | | 39 | 337 | 86 | 7 | 427 |
| Psespi 33 | 0.2273 | | 49 | 414 | 124 | 7 | 653 |
| Psespi 35 | 0.0466 | | 35 | 265 | 148 | | 514 |
| Psespi 38 | 0.1395 | | 35 | 265 | 131 | 6 | 477 |
| Psespi 39 | 0.1914 | | 48 | 357 | 112 | 7 | 462 |
| Wheat 1 | 0.3819 | | 33 | 247 | 119 | 5 | 452 |
| Wheat 3 | 0.488 | | 17 | 124 | 145 | 2 | 416 |
| Wheat 4 | 0.5109 | | 7 | 26 | 28 | | 82 |
| Wheat 16 | 0.4621 | | 51 | 394 | 136 | 7 | 562 |
| Wheat 17 | 0.2874 | | 61 | 1065 | 121 | 13 | 445 |
| Wheat 18 | 0.409 | | 35 | 306 | 123 | 5 | 488 |
| Wheat 19 | 0.4835 | | 37 | 351 | 126 | 7 | 546 |
| Wheat 21 | 0.3734 | 10 | 100 | 668 | 108 | 9 | 227 |
| Wheat 23 | 0.5071 | 32 | 35 | 822 | 76 | 7 | 405 |
| Wheat 39 | 0.146 | | 159 | 1484 | 129 | 32 | 643 |

Table 9. Uncorrected ICP-OES concentrations. Units are in mg $L^{-1}$. Bold numbers = below detection limit

| Sample | As | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|
| Artlud 9 | **0.1** | 0.398 | 2.42 | 1.43 | 0.0487 | 3.45 |
| Artlud 12 | **0.1** | 0.329 | 1.35 | 0.741 | **0.0237** | 2.67 |
| Artlud 13 | **0.1** | 0.401 | 1.87 | 1.69 | 0.0318 | 3.83 |
| Artlud 14 | **0.1** | 0.244 | 0.987 | 0.762 | **0.0237** | 3.01 |
| Artlud 15 | **0.1** | 0.317 | 1.50 | 0.793 | 0.0257 | 3.59 |
| Artlud 17 | **0.1** | 0.139 | 0.442 | 0.294 | **0.0237** | 1.05 |
| Artlud 25 | **0.1** | 0.308 | 2.84 | 1.37 | 0.0711 | 2.27 |
| Artlud 28 | **0.1** | 0.197 | 1.74 | 1.24 | 0.0406 | 3.17 |
| Artlud 37 | **0.1** | 0.454 | 1.38 | 2.51 | **0.0237** | 4.61 |
| Artlud 39 | **0.1** | 0.523 | 2.26 | 3.02 | 0.0447 | 4.68 |
| Hemp 2 | **0.1** | 0.160 | 0.726 | 0.838 | **0.0237** | 1.66 |
| Hemp 3 | **0.1** | 0.546 | 1.74 | 2.24 | 0.0305 | 5.16 |
| Hemp 10 | 0.118 | 0.488 | 9.05 | 1.74 | 0.0679 | 3.21 |
| Hemp 16 | **0.1** | 0.0922 | 0.196 | 0.257 | **0.0237** | 0.747 |
| Hemp 18 | **0.1** | 0.334 | 0.609 | 0.621 | **0.0237** | 2.62 |
| Hemp 28 | 4.63 | 14.6 | 40.0 | 4.30 | 3.49 | 570 |
| Hemp 29 | 0.137 | 1.09 | 4.20 | 1.02 | 0.104 | 8.63 |
| Hemp 34 | 0.186 | 1.10 | 8.71 | 2.54 | 0.161 | 10.1 |
| Hemp 36 | **0.1** | 0.430 | 1.76 | 0.508 | 0.0346 | 2.57 |
| Hemp 39 | 0.162 | 0.630 | 3.22 | 1.17 | 0.0590 | 7.62 |
| Psespi 1 | **0.1** | 0.150 | 2.03 | 0.704 | 0.0421 | 1.90 |
| Psespi 4 | 0.102 | 0.378 | 3.27 | 1.18 | 0.0578 | 4.99 |
| Psespi 14 | **0.1** | 0.269 | 2.05 | 0.714 | 0.0415 | 3.16 |
| Psespi 16 | **0.1** | 0.381 | 2.11 | 1.10 | 0.0359 | 4.11 |
| Psespi 31 | **0.1** | 0.203 | 1.20 | 0.652 | 0.0280 | 2.53 |
| Psespi 32 | **0.1** | 0.241 | 2.08 | 0.534 | 0.0407 | 2.64 |
| Psespi 33 | **0.1** | 0.369 | 3.14 | 0.936 | 0.0520 | 4.95 |
| Psespi 35 | **0.1** | 0.0542 | 0.412 | 0.230 | **0.0237** | 0.799 |
| Psespi 38 | **0.1** | 0.164 | 1.23 | 0.607 | 0.0299 | 2.22 |
| Psespi 39 | **0.1** | 0.304 | 2.28 | 0.715 | 0.0460 | 2.95 |
| Wheat 1 | **0.1** | 0.426 | 3.14 | 1.51 | 0.0636 | 5.75 |
| Wheat 3 | **0.1** | 0.271 | 2.02 | 2.36 | 0.0262 | 6.76 |
| Wheat 4 | **0.1** | 0.122 | 0.450 | 0.477 | **0.0237** | 1.40 |
| Wheat 16 | **0.1** | 0.778 | 6.07 | 2.10 | 0.108 | 8.65 |
| Wheat 17 | **0.1** | 0.584 | 10.2 | 1.16 | 0.123 | 4.26 |
| Wheat 18 | **0.1** | 0.481 | 4.17 | 1.68 | 0.0738 | 6.65 |
| Wheat 19 | **0.1** | 0.602 | 5.66 | 2.03 | 0.109 | 8.80 |
| Wheat 21 | 0.122 | 1.24 | 8.31 | 1.34 | 0.116 | 2.83 |
| Wheat 23 | 0.540 | 0.586 | 13.9 | 1.28 | 0.113 | 6.84 |
| Wheat 39 | **0.1** | 0.774 | 7.22 | 0.629 | 0.154 | 3.13 |

Table 10. Phytoextraction potential (%) calculated from ICP-OES data.

| Sample | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|
| Artlud 9 | 0.019% | 0.001% | 0.101% | 0.002% | 0.017% |
| Artlud 12 | 0.016% | 0.001% | 0.052% | 0.000% | 0.013% |
| Artlud 13 | 0.019% | 0.001% | 0.119% | 0.001% | 0.019% |
| Artlud 14 | 0.011% | 0.000% | 0.054% | 0.000% | 0.015% |
| Artlud 15 | 0.015% | 0.001% | 0.056% | 0.001% | 0.018% |
| Artlud 17 | 0.007% | 0.000% | 0.021% | 0.000% | 0.005% |
| Artlud 25 | 0.015% | 0.001% | 0.096% | 0.003% | 0.011% |
| Artlud 28 | 0.009% | 0.001% | 0.087% | 0.002% | 0.016% |
| Artlud 37 | 0.021% | 0.001% | 0.176% | 0.000% | 0.023% |
| Artlud 39 | 0.025% | 0.001% | 0.212% | 0.002% | 0.023% |
| Hemp 2 | 0.008% | 0.000% | 0.059% | 0.000% | 0.008% |
| Hemp 3 | 0.026% | 0.001% | 0.158% | 0.001% | 0.026% |
| Hemp 10 | 0.023% | 0.004% | 0.122% | 0.003% | 0.016% |
| Hemp 16 | 0.004% | 0.000% | 0.018% | 0.000% | 0.004% |
| Hemp 18 | 0.016% | 0.000% | 0.044% | 0.000% | 0.013% |
| Hemp 28 | 0.688% | 0.019% | 0.302% | 0.132% | 2.825% |
| Hemp 29 | 0.051% | 0.002% | 0.072% | 0.004% | 0.043% |
| Hemp 34 | 0.052% | 0.004% | 0.179% | 0.006% | 0.050% |
| Hemp 36 | 0.020% | 0.001% | 0.036% | 0.001% | 0.013% |
| Hemp 39 | 0.030% | 0.002% | 0.082% | 0.002% | 0.038% |
| Psespi 1 | 0.007% | 0.001% | 0.050% | 0.002% | 0.009% |
| Psespi 4 | 0.018% | 0.002% | 0.083% | 0.002% | 0.025% |
| Psespi 14 | 0.013% | 0.001% | 0.050% | 0.002% | 0.016% |
| Psespi 16 | 0.018% | 0.001% | 0.077% | 0.001% | 0.020% |
| Psespi 31 | 0.010% | 0.001% | 0.046% | 0.001% | 0.013% |
| Psespi 32 | 0.011% | 0.001% | 0.038% | 0.002% | 0.013% |
| Psespi 33 | 0.017% | 0.001% | 0.066% | 0.002% | 0.025% |
| Psespi 35 | 0.003% | 0.000% | 0.016% | 0.000% | 0.004% |
| Psespi 38 | 0.008% | 0.001% | 0.043% | 0.001% | 0.011% |
| Psespi 39 | 0.014% | 0.001% | 0.050% | 0.002% | 0.015% |
| Wheat 1 | 0.020% | 0.001% | 0.106% | 0.002% | 0.028% |
| Wheat 3 | 0.013% | 0.001% | 0.166% | 0.001% | 0.034% |
| Wheat 4 | 0.006% | 0.000% | 0.034% | 0.000% | 0.007% |
| Wheat 16 | 0.037% | 0.003% | 0.148% | 0.004% | 0.043% |
| Wheat 17 | 0.028% | 0.005% | 0.082% | 0.005% | 0.021% |
| Wheat 18 | 0.023% | 0.002% | 0.118% | 0.003% | 0.033% |
| Wheat 19 | 0.028% | 0.003% | 0.143% | 0.004% | 0.044% |
| Wheat 21 | 0.058% | 0.004% | 0.094% | 0.004% | 0.014% |
| Wheat 23 | 0.028% | 0.007% | 0.090% | 0.004% | 0.034% |
| Wheat 39 | 0.036% | 0.003% | 0.044% | 0.006% | 0.016% |

Table 11. Bioconcentration factor calculated from ICP-OES data. Blanks cells = not calculated

| Sample | Cu | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|
| Artlud 9 | 0.158229 | 0.009689 | 0.848304 | 0.015565 | 0.144244 |
| Artlud 12 | 0.344078 | 0.014218 | 1.156353 | | 0.293662 |
| Artlud 13 | 1.167585 | 0.054833 | 7.342471 | 0.074439 | 1.172785 |
| Artlud 14 | 0.409294 | 0.016673 | 1.907269 | | 0.530991 |
| Artlud 15 | 0.410742 | 0.019573 | 1.533186 | 0.026771 | 0.489193 |
| Artlud 17 | 0.442431 | 0.014168 | 1.396335 | | 0.351476 |
| Artlud 25 | 0.203398 | 0.018887 | 1.349979 | 0.037748 | 0.157651 |
| Artlud 28 | 0.140997 | 0.012542 | 1.324271 | 0.023361 | 0.238604 |
| Artlud 37 | 0.260241 | 0.007966 | 2.146863 | | 0.277905 |
| Artlud 39 | 0.204435 | 0.008897 | 1.761459 | 0.014047 | 0.192387 |
| Hemp 2 | 0.249598 | 0.011406 | 1.950639 | | 0.272336 |
| Hemp 3 | 0.330149 | 0.010596 | 2.021047 | 0.014827 | 0.328127 |
| Hemp 10 | 0.357255 | 0.066721 | 1.900726 | 0.039963 | 0.247138 |
| Hemp 16 | 0.572709 | 0.012261 | 2.382031 | | 0.487977 |
| Hemp 18 | 0.59225 | 0.010875 | 1.643092 | | 0.48858 |
| Hemp 28 | 3.116143 | 0.085977 | 1.369445 | 0.598851 | 12.79425 |
| Hemp 29 | 0.675426 | 0.02621 | 0.943111 | 0.05181 | 0.56239 |
| Hemp 34 | 0.560897 | 0.044727 | 1.932573 | 0.066 | 0.541611 |
| Hemp 36 | 0.849157 | 0.035002 | 1.496906 | 0.054932 | 0.533738 |
| Hemp 39 | 0.463861 | 0.023876 | 1.285419 | 0.034924 | 0.590035 |
| Psespi 1 | 0.097425 | 0.013278 | 0.682282 | 0.021983 | 0.12978 |
| Psespi 4 | 0.122021 | 0.01063 | 0.568377 | 0.015 | 0.169402 |
| Psespi 14 | 0.14412 | 0.011061 | 0.570797 | 0.017875 | 0.178047 |
| Psespi 16 | 0.149958 | 0.008363 | 0.646026 | 0.01136 | 0.170123 |
| Psespi 31 | 0.132016 | 0.007859 | 0.632688 | 0.014639 | 0.173032 |
| Psespi 32 | 0.133299 | 0.011586 | 0.440721 | 0.018098 | 0.153564 |
| Psespi 33 | 0.166385 | 0.014259 | 0.629759 | 0.01885 | 0.23473 |
| Psespi 35 | 0.119207 | 0.009125 | 0.754814 | | 0.184809 |
| Psespi 38 | 0.120491 | 0.009101 | 0.665446 | 0.017661 | 0.17153 |
| Psespi 39 | 0.162786 | 0.012295 | 0.571297 | 0.019803 | 0.166128 |
| Wheat 1 | 0.114326 | 0.008486 | 0.60468 | 0.013722 | 0.162286 |
| Wheat 3 | 0.056916 | 0.004272 | 0.739589 | 0.004424 | 0.14931 |
| Wheat 4 | 0.024474 | 0.000909 | 0.142784 | | 0.029536 |
| Wheat 16 | 0.172556 | 0.013558 | 0.694995 | 0.019258 | 0.201763 |
| Wheat 17 | 0.208263 | 0.036632 | 0.617262 | 0.035264 | 0.159766 |
| Wheat 18 | 0.120534 | 0.010523 | 0.62818 | 0.014868 | 0.175251 |
| Wheat 19 | 0.127611 | 0.012083 | 0.642093 | 0.018576 | 0.196177 |
| Wheat 21 | 0.340357 | 0.022971 | 0.548818 | 0.025598 | 0.081691 |
| Wheat 23 | 0.118438 | 0.028292 | 0.386024 | 0.018361 | 0.145387 |
| Wheat 39 | 0.543344 | 0.051042 | 0.658864 | 0.086913 | 0.231075 |

Table 12. Weekly plant growth data for *Cannabis sativa*. Units are in cm. DEAD = when the replication died; blank cells mean no measurement.

| Sample | Day 14 | Day 21 | Day 28 | Day 35 | Day 56 | Day 63 | Day 70 | Day 77 | Day 84 |
|---|---|---|---|---|---|---|---|---|---|
| Hemp 1 | 3 | 5.6 | 6.5 | 7 | | DEAD | | | |
| Hemp 2 | 2.7 | 4.3 | 4.7 | 6.1 | 9.3 | 9.7 | 10.3 | 10.2 | 11 |
| Hemp 3 | | 4.1 | 5.7 | 9.6 | 12.1 | 12.2 | 12.6 | 12.6 | 12.7 |
| Hemp 4 | 2.4 | 5.1 | 7.4 | 8.4 | 10.4 | 10.6 | 9.2 | 9.6 | |
| Hemp 5 | 2.1 | 4.2 | 5.8 | 6.7 | | | | | |
| Hemp 6 | 4.2 | 6.5 | 7.2 | 7.3 | 7.7 | 9.4 | 8 | 8 | 8 |
| Hemp 7 | 3.5 | 5.4 | 5.6 | 5.5 | | DEAD | | | |
| Hemp 8 | 1.6 | 2.2 | 3.6 | 4.1 | 4.9 | DEAD | | | |
| Hemp 9 | 4.1 | 6.6 | 8.1 | 8.3 | DEAD | DEAD | | | |
| Hemp 10 | 4.2 | 5.7 | 5.4 | 8.2 | 10.7 | 10.4 | 10.8 | 11.9 | 11.9 |
| Hemp 11 | 3 | 6.4 | 10.5 | 25.6 | 38.7 | 36.6 | 37.7 | | |
| Hemp 12 | 3.1 | 5.5 | 6.7 | 8 | 12 | 12.5 | 13.1 | 13.1 | 13.3 |
| Hemp 13 | 2.4 | 5.5 | 7.2 | 11.3 | 15.1 | 15.4 | 16.3 | 16.2 | 16.2 |
| Hemp 14 | 2.1 | 4.6 | 6.3 | 13.4 | 20.4 | 20.5 | 20.7 | 21.1 | 21.2 |
| Hemp 15 | 2.9 | 5.4 | 6.8 | 7.5 | 9.1 | 9.1 | 10 | 10.1 | 9.7 |
| Hemp 16 | 3.1 | 6.5 | 8.6 | 16.4 | 20.6 | 20.5 | | | |
| Hemp 17 | 4.1 | 5.6 | 8.9 | 13.4 | 14.2 | 14.4 | | | |
| Hemp 18 | 1.9 | 5.3 | 10.6 | 22.6 | 25.1 | DEAD | | | |
| Hemp 19 | 2.6 | 5.8 | 9.8 | 21.5 | 24.7 | DEAD | | | |
| Hemp 20 | 2.1 | 4.6 | 8.1 | 27.3 | 32.5 | 32.3 | 32.5 | | |
| Hemp 21 | 2 | 5 | 6.9 | 13 | 19.9 | 21 | 21.3 | 21.1 | 21.3 |
| Hemp 22 | 1.8 | 5.5 | 9.2 | 16.5 | 22.6 | 22.8 | 23.1 | 22.8 | 22.9 |
| Hemp 23 | 1.6 | 4.8 | 6.6 | 11 | 16 | 16.1 | 16.3 | 16.4 | 16.3 |
| Hemp 24 | 3.7 | 6 | 9.1 | 16.25 | 20.3 | 21.2 | 21.1 | 21.8 | 21.2 |
| Hemp 25 | 3.1 | 5.3 | 8 | 22.5 | 34.8 | 34.8 | | | |
| Hemp 26 | 2.1 | 4.7 | 9.8 | 13.5 | 31 | 29.5 | | | |
| Hemp 27 | 2.1 | 4.4 | 7.6 | 14.8 | 21.7 | 22 | 22.2 | 22.3 | 21.8 |
| Hemp 28 | 2.3 | 4.6 | 7.7 | 15.7 | 23.1 | 23.4 | 23.4 | 24.6 | 24.6 |
| Hemp 29 | | 4.8 | 8.2 | 21 | 42.5 | 42.7 | 42.6 | | |
| Hemp 30 | 1.4 | 3.6 | 6.5 | 14.2 | 12.6 | 17.6 | 17.9 | 18 | 18.1 |
| Hemp 31 | 2.5 | 6.5 | 8.6 | 18 | 22.5 | DEAD | | | |
| Hemp 32 | 1.6 | 5 | 5.4 | 5.5 | DEAD | DEAD | | | |
| Hemp 33 | 2.4 | 5.3 | 7.3 | 11.3 | 18.8 | 19 | 19.1 | 19 | 20 |
| Hemp 34 | 1.9 | 4 | 5.5 | 8.2 | 13 | 13.6 | 13.7 | 13.7 | 13.6 |
| Hemp 35 | 1.4 | 5.5 | 9.7 | 18.1 | 32.1 | 33 | 32.6 | | |
| Hemp 36 | 1.3 | 4 | 9.2 | 11.4 | 22.6 | 23.4 | | | |
| Hemp 37 | | 3.5 | 5.6 | 12.1 | 41 | 41.7 | 42.1 | | |
| Hemp 38 | 2.7 | 7.4 | 14.2 | 20.4 | 23.7 | 24.1 | 24.8 | 25 | 25.1 |
| Hemp 39 | 3 | 6.8 | 11.5 | 26 | 32.5 | 32.2 | | | |
| Hemp 40 | 2.6 | 5 | 9.8 | 21.9 | 32.1 | 31.8 | 31.5 | | |

Table 13. Weekly plant growth data for *Artemisia ludoviciana*. Units are in cm. DEAD = when the replication died; blank cells mean no measurement.

| Sample | Day 14 | Day 21 | Day 28 | Day 35 | Day 56 | Day 63 | Day 70 | Day 77 | Day 84 |
|---|---|---|---|---|---|---|---|---|---|
| Artlud 1 | 0.3 | 0.6 | 0.8 | 3.5 | 8.3 | 9.8 | 11.8 | 14.5 | 16.4 |
| Artlud 2 | 0.4 | 0.7 | 0.8 | DEAD | | | | | |
| Artlud 3 | 0.4 | 1.1 | 1.5 | 5.9 | 10.6 | 12.1 | 13.2 | 15.5 | 16.7 |
| Artlud 4 | 0.3 | 0.5 | 0.9 | 1.6 | 5.4 | 6.5 | 8 | 9.6 | 11.7 |
| Artlud 5 | 0.6 | 0.9 | 2.5 | 8.9 | 16.8 | 18 | 18.9 | 19.5 | 21.8 |
| Artlud 6 | 0.4 | 1.1 | 2.3 | 8.6 | 14.7 | 17.5 | 18.2 | 19.7 | 20 |
| Artlud 7 | 0.5 | 0.6 | 1.1 | 3.6 | 10.3 | 12.8 | 13.6 | 15.6 | 16.2 |
| Artlud 8 | 0.6 | 1.2 | 1.9 | 9.6 | 17.5 | 19.2 | 19.7 | 20.7 | 21 |
| Artlud 9 | 0.5 | 0.7 | 1.4 | 6.9 | 15.6 | 18.3 | 18.6 | 20.7 | 22.1 |
| Artlud 10 | 0.4 | 1 | 1.3 | 7 | 13.4 | 14.9 | 16.8 | 18.5 | 19.6 |
| Artlud 11 | 0.2 | 0.5 | 0.6 | 1.6 | 3 | 3.1 | 3.6 | 4 | 4.3 |
| Artlud 12 | 0.4 | 0.7 | 1.1 | 3.4 | 8.6 | 10 | 10.1 | 10.5 | 10.6 |
| Artlud 13 | 0.4 | 0.8 | 1.2 | 4.2 | 9 | 11.5 | 13.5 | 16 | 18 |
| Artlud 14 | 0.5 | 0.6 | 1.1 | 3.3 | 7.1 | 8.4 | 9.2 | 11.2 | 11.9 |
| Artlud 15 | 0.3 | 0.6 | 1 | 5 | 8.7 | 8.8 | 9.1 | 9.5 | 9.8 |
| Artlud 16 | 0.6 | 0.5 | 0.6 | DEAD | | | | | |
| Artlud 17 | 0.4 | 0.8 | 0.9 | 3.7 | 7.6 | 9.1 | 9 | 9.6 | 10.2 |
| Artlud 18 | 0.4 | 1.1 | 0.9 | 1 | DEAD | | | | |
| Artlud 19 | 0.3 | 0.7 | 1.2 | 5.7 | 12.5 | 14.6 | 15.4 | 18 | 19.6 |
| Artlud 20 | 0.4 | 1 | 1.3 | 5.4 | 7.4 | 8.3 | 8 | 8.1 | 7.7 |
| Artlud 21 | 0.4 | 0.5 | 0.7 | 2 | 8.7 | 7.5 | 8.1 | 9.3 | 10.7 |
| Artlud 22 | 0.3 | 0.6 | 1 | 5.5 | 12 | 15.6 | 16.2 | 17.6 | 18.5 |
| Artlud 23 | 0.4 | 1 | 1.5 | 5.7 | 12.1 | 15.4 | 16.3 | 17.5 | 18.6 |
| Artlud 24 | 0.4 | 0.8 | 1.1 | 4.9 | 11.3 | 14 | 15.2 | 16.9 | 18.5 |
| Artlud 25 | 0.3 | 1 | 1.2 | 3.1 | 10.2 | 10.7 | 11.2 | 12.7 | 13.3 |
| Artlud 26 | 0.3 | 0.7 | 0.7 | 1.5 | 4 | 5.3 | 6.4 | 8.1 | 10 |
| Artlud 27 | 0.2 | 0.7 | 1.5 | 4.6 | 9.9 | 12 | 12.5 | 14.1 | 15.3 |
| Artlud 28 | 0.4 | 0.4 | 1.1 | 2 | 6.1 | 8.7 | 9.1 | 10.2 | 10.7 |
| Artlud 29 | 0.4 | 0.8 | 1.3 | 5.3 | 12.2 | 16.8 | 17.6 | 19.4 | 20.4 |
| Artlud 30 | 0.3 | 0.4 | 0.8 | 1.2 | 3 | 5.2 | 5.6 | 7 | 8.3 |
| Artlud 31 | 0.3 | 0.4 | 0.7 | 1.5 | 6.7 | 8.7 | 10.4 | 13.2 | 14.1 |
| Artlud 32 | 0.3 | 0.5 | 1.1 | 5.5 | 13.6 | 15.4 | 15.6 | 17.9 | 20.7 |
| Artlud 33 | 0.2 | 0.5 | 1.5 | 6.1 | 15 | 16.4 | 16.7 | 18.9 | 17.9 |
| Artlud 34 | 0.4 | 0.7 | 1.4 | 5.3 | 11.7 | 13.8 | 14.6 | 16.6 | 18 |
| Artlud 35 | 0.2 | 0.5 | 1.1 | 6.4 | 15.6 | 17.7 | 18.3 | 20.8 | 22.4 |
| Artlud 36 | 0.4 | 0.6 | 1 | 4.5 | 11.3 | 12.3 | 14.2 | 17.2 | 18.1 |
| Artlud 37 | 0.3 | 1 | 0.7 | 2.6 | 8.9 | 10.8 | 12.2 | 14.7 | 16 |
| Artlud 38 | 0.2 | 0.8 | 1.5 | 4 | 13.4 | 12.2 | 13.1 | 15.2 | 17.1 |
| Artlud 39 | 0.5 | 0.8 | 1.6 | 2 | 13.6 | 15.6 | 16.1 | 17.8 | 19.4 |
| Artlud 40 | 0.3 | 0.6 | 1.1 | 4.8 | 10.9 | 12.3 | 13.5 | 16.3 | 18.1 |

Table 14. Weekly plant growth data for *Triticum aestivum*. Units are in cm. DEAD = when the replication died; blank cells mean no measurement.

| Sample | Day 14 | Day 21 | Day 28 | Day 35 | Day 56 | Day 63 | Day 70 | Day 77 | Day 84 |
|---|---|---|---|---|---|---|---|---|---|
| Wheat 1 | | 5 | 19.8 | 40.9 | 61.1 | 60.6 | 60.3 | 60.1 | 60 |
| Wheat 2 | 11.3 | 25.7 | 37.3 | 44.1 | 60.1 | 60 | 58.7 | 59.1 | 59.1 |
| Wheat 3 | 20.6 | 32.1 | 33.8 | 37.6 | 45.6 | 44.9 | 44.6 | 44.2 | 43.7 |
| Wheat 4 | 9.1 | 27.7 | 38.3 | 47.6 | 47.4 | 47 | 46.8 | 46.5 | 46.7 |
| Wheat 5 | 21.5 | 35.8 | 42.1 | 48.4 | 55.2 | 54.8 | 54.7 | 54.3 | 54.3 |
| Wheat 6 | 17 | 36.5 | 42 | 45.4 | 51.5 | 51 | 51 | 50.5 | 50.4 |
| Wheat 7 | 19.4 | 37.4 | 44.2 | 46.7 | 46.8 | 46.5 | 46.4 | 46.4 | 46.3 |
| Wheat 8 | | 15.2 | 34 | 47.3 | 55 | 54.8 | 54.6 | 54.5 | 54.3 |
| Wheat 9 | 4.5 | 21.7 | 33.7 | 39.9 | 49.6 | 50.3 | 50.3 | 50.3 | 49.9 |
| Wheat 10 | | | 8.2 | 32.2 | 56.5 | 55.9 | 55.6 | 55.5 | 55.4 |
| Wheat 11 | | | 7.5 | 27.3 | 43 | 43.5 | 43.8 | 43.5 | 43.3 |
| Wheat 12 | 18.4 | 35.8 | 41 | 47.4 | 55.1 | 54.8 | 54.4 | 54.5 | 51.2 |
| Wheat 13 | 14.6 | 30.6 | 40.6 | 49.2 | 53.4 | 54.9 | 58.4 | 54.5 | 55.7 |
| Wheat 14 | 19.7 | 35.2 | 40.5 | 41.1 | 48.2 | 47.4 | 47.5 | 47.5 | 57.4 |
| Wheat 15 | 12.9 | 26.9 | 36.8 | 44 | 54.3 | 53.6 | 54.5 | 54.7 | 54.1 |
| Wheat 16 | 14.8 | 26.9 | 35 | 35 | 44.6 | 43.6 | 44.4 | 44.3 | 44.2 |
| Wheat 17 | 15.1 | 31.8 | 35.8 | 39.2 | 44.1 | 43.6 | 43.9 | 43.2 | 43.3 |
| Wheat 18 | 13.9 | 29.7 | 32.7 | 37.5 | 46.2 | 45.8 | 45.6 | 45.9 | 45.8 |
| Wheat 19 | 12.4 | 27.3 | 35.9 | 47.7 | 41.1 | 43.9 | 41 | 56.7 | 43.4 |
| Wheat 20 | 11.6 | 24.6 | 41 | 48 | 56.4 | 58.5 | 58.4 | 57.1 | 57.3 |
| Wheat 21 | 10.5 | 22.1 | 34.5 | 44.5 | 51.5 | 50.9 | 51.1 | 50.6 | 50.8 |
| Wheat 22 | 9 | 22 | 29 | 41.8 | 47.6 | 49.3 | 49.3 | 46.2 | 48.8 |
| Wheat 23 | 12.5 | 26.1 | 35.1 | 45.3 | 54 | 53.2 | 52.9 | 52.5 | 52.4 |
| Wheat 24 | 17.9 | 40 | 44.8 | 52.5 | 56.3 | 55.6 | 55.5 | 55.2 | 54.8 |
| Wheat 25 | 18.5 | 40.5 | 48.2 | 54.5 | 56 | 52.9 | 53.1 | 52.6 | 52.6 |
| Wheat 26 | 10 | 15.6 | 25.7 | 37.8 | 55.7 | 60 | 59.6 | 58.3 | 58.6 |
| Wheat 27 | 12.5 | 30.8 | 42.7 | 54.6 | 52.2 | 55.9 | 55.7 | 55.5 | 54.3 |
| Wheat 28 | 0 | 4.5 | 14.2 | 29 | 37.1 | 42.3 | 44.8 | 44.8 | 44.9 |
| Wheat 29 | 17.5 | 35.6 | 45.2 | 50.5 | 60.6 | 59.6 | 59.6 | 59.4 | 59.5 |
| Wheat 30 | 9.5 | 24.6 | 36.6 | 44.2 | 56.8 | 58.4 | 58.3 | 57.7 | 57.2 |
| Wheat 31 | 13.9 | 29.8 | 42.5 | 47.5 | 58.1 | 57.3 | 56.5 | 57.1 | 56.3 |
| Wheat 32 | 13.2 | 26.3 | 38.9 | 49.5 | 55.1 | 55.4 | 54.6 | 55.1 | 54.9 |
| Wheat 33 | 23.7 | 45.7 | 49 | 49.5 | 58.1 | 58.2 | 58.1 | 57.6 | 57.8 |
| Wheat 34 | 19.6 | 40 | 45.8 | 45.3 | 49.7 | 49.2 | 48.7 | 48.2 | 48.4 |
| Wheat 35 | 22.8 | 30 | 41.5 | 41 | 45 | 44.6 | 44.2 | 43.6 | 43.5 |
| Wheat 36 | 15 | 35.9 | 42.7 | 46.2 | 50.1 | 49.6 | 48.2 | 49.6 | 49.4 |
| Wheat 37 | 21.5 | 31.3 | 34.4 | 39.2 | 42.8 | 42.2 | 42.4 | 41.8 | 41.8 |
| Wheat 38 | 12.9 | 27.7 | 32.3 | 45.2 | 55.9 | 56.3 | 56.1 | 55.8 | 50.2 |
| Wheat 39 | 8 | 12.2 | 18.7 | 33.1 | 54.5 | 53.8 | 53.1 | 53.1 | 53.1 |
| Wheat 40 | 8.5 | 8.6 | 8.6 | 9 | 27.8 | 31.6 | 31.6 | 42 | 31.8 |

Table 125. Weekly plant growth data for *Pseudoroegnaria spicata*. Units are in cm. DEAD = when the replication died; blank cells mean no measurement.

| Sample | Day 14 | Day 21 | Day 28 | Day 35 | Day 56 | Day 63 | Day 70 | Day 77 | Day 84 |
|---|---|---|---|---|---|---|---|---|---|
| Psespi 1 | 12.3 | 14.6 | 18 | 23 | 30.1 | 34.3 | 34.1 | 35.5 | 35.5 |
| Psespi 2 | 11.7 | 11.8 | 23.4 | 33.5 | 42.3 | 44.1 | 47.7 | 47.7 | 47.5 |
| Psespi 3 | 10.1 | 17.8 | 23 | 26.5 | 43.1 | 43.3 | 43.2 | 42.8 | 47.6 |
| Psespi 4 | | 3.4 | 10.2 | 20.9 | 36.4 | 39.9 | 40.1 | 41.4 | 45.6 |
| Psespi 5 | | | | 9.3 | 29.1 | 32.2 | 34.1 | 41 | 41.8 |
| Psespi 6 | 15.3 | 20.2 | 28.4 | 36.4 | 45.9 | 45.3 | 45.3 | 45.4 | 47.7 |
| Psespi 7 | | 11.9 | 19.1 | 26.1 | 42.5 | 42.5 | 45.4 | 47.8 | 49.5 |
| Psespi 8 | | 14.7 | 20.6 | 29.6 | 41.9 | 41.8 | 41.8 | 41.7 | 41.6 |
| Psespi 9 | 5.2 | 10.2 | 13.9 | 22.1 | 31.3 | 31.1 | 31.1 | 31.1 | 31.1 |
| Psespi 10 | 9.6 | 12.5 | 16.8 | 27.6 | 34.5 | 37 | 36.8 | 36.6 | 36.5 |
| Psespi 11 | 11.9 | 17.1 | 22 | 32.7 | 43.6 | 47.9 | 47.6 | 47.7 | 47.1 |
| Psespi 12 | 7 | 13.7 | 17.1 | 22 | 33.6 | 35.4 | 35.4 | 35.7 | 36.6 |
| Psespi 13 | 9.1 | 16.7 | 23.5 | 30.2 | 47.1 | 46.8 | 46.5 | 46.4 | 46.3 |
| Psespi 14 | 16.6 | 17.8 | 24.7 | 31.3 | 38.4 | 38.8 | 38.5 | 38.9 | 38.7 |
| Psespi 15 | 7.2 | 17.2 | 24.9 | 32.6 | 43.5 | 43.5 | 43.5 | 43.4 | 43.3 |
| Psespi 16 | 7.1 | 14 | 20.8 | 29.5 | 38.8 | 40.8 | 43.9 | 46.3 | 46.1 |
| Psespi 17 | 7.6 | 13.5 | 19.2 | 26.3 | 38.8 | 44.3 | 44.1 | 44.1 | 43.9 |
| Psespi 18 | 12.3 | 18.9 | 14.4 | 30.9 | 41.7 | 41.6 | 41.6 | 41.5 | 41.3 |
| Psespi 19 | 14 | 22.1 | 28.4 | 36.9 | 51 | 51.7 | 51.6 | 51.2 | 51.1 |
| Psespi 20 | 12.6 | 20.5 | 14.1 | 31.6 | 41.7 | 43 | 38.4 | 39.4 | 39.2 |
| Psespi 21 | 12 | 16.3 | 16.2 | 24.5 | 37.5 | 40.6 | 40.4 | 39.7 | 43.4 |
| Psespi 22 | 10.5 | 18.7 | 22.1 | 35.3 | 45 | 48.2 | 48.2 | 48.1 | 48 |
| Psespi 23 | 8.5 | 14.5 | 17.8 | 24 | 33 | 32.9 | 32.8 | 32.4 | 32.6 |
| Psespi 24 | 9 | 12.4 | 15.1 | 16 | 38 | 27.9 | 38.8 | 40 | 40.4 |
| Psespi 25 | | | | | | | | | |
| Psespi 26 | 11.5 | 16.2 | 21.7 | 28.4 | 34.9 | 37.2 | 36.8 | 37 | 37 |
| Psespi 27 | 11.5 | 17.3 | 22.1 | 27 | 36.2 | 36.1 | 36.1 | 38.5 | 39.1 |
| Psespi 28 | 8.7 | 15.9 | 20.1 | 32.9 | 45.4 | 48.5 | 48.6 | 48.4 | 48.3 |
| Psespi 29 | 14 | 20.6 | 22.4 | 30.9 | 39.1 | 39.1 | 43.1 | 48.9 | 48.4 |
| Psespi 30 | 7 | 16 | 20.5 | 29.4 | 43 | 43 | 42.9 | 43.3 | 47.6 |
| Psespi 31 | 14 | 17.5 | 16.7 | 18.9 | 26.4 | 27.4 | 27.4 | 27.3 | 27.5 |
| Psespi 32 | 6 | 14 | 16.6 | 22 | 40.8 | 40.1 | 40.4 | 40.2 | 40.1 |
| Psespi 33 | 11 | 16.1 | 22.9 | 30.3 | 48.4 | 49.1 | 49.3 | 49.4 | 49.1 |
| Psespi 34 | 13.8 | 20.1 | 24 | 28.6 | 40 | 39.9 | 39.8 | 39.8 | 39.7 |
| Psespi 35 | | | 5 | 12.7 | 22 | 24.6 | 23.7 | 27.1 | 28.5 |
| Psespi 36 | | | 4.2 | 12 | 22.7 | 24.8 | 27.2 | 28.3 | 30.5 |
| Psespi 37 | | | | 1.7 | 12.8 | 17.5 | 17.3 | 18.1 | 20.4 |
| Psespi 38 | 11.2 | 14.6 | 20.4 | 25.2 | 39.7 | 40.9 | 40.9 | 40.7 | 40.6 |
| Psespi 39 | 11.9 | 17.7 | 21.9 | 28.4 | 45.4 | 45 | 45.1 | 44.9 | 44.9 |
| Psespi 40 | 12 | 19.8 | 24.7 | 30.5 | 44.2 | 43.9 | 44.4 | 44.1 | 44 |