Alternative Agricultural Land Clearing Practices for the Territories to Reduce Greenhouse Gas Emissions and Build Northern Soils

Results of a field trial, 2020-2022

Revised, September 2024

Recommended Citation:

Pugh, R. Alternative Agricultural Land Clearing Practices for the Territories to Reduce Greenhouse Gas Emissions and Build Northern Soils: Results of a field trial, 2020-22. YukonU Research Centre, Yukon University, 2024, 1-33p.

Photo Credit: Rachel Pugh

CANADIAN AGRICULTURAL PARTNERSHIP

Yukon

Agriculture and Agri-Food Canada

Project Team

Lead Author

Rachel Pugh YukonU Research Centre

Contributors

Jonathan Lucas Project Lead, Government of Yukon, Agriculture Branch
Lori Phillips Agriculture and Agri-Food Canada, Harrow Research and Development Centre

All photo credits to the author, except where indicated.

Revised Version

An earlier version of this report was released July 2024 with edits and alterations which were not reviewed and approved by the author. This current report has been revised in a manner agreeable to the author and the project lead.

Acknowledgments

Funding for this project came from Agriculture and Agrifood Canada's Canadian Agricultural Partnerships program.

This field study was designed by Jonathan Lucas (Project Lead) of Yukon Government Agriculture Branch, with contributions from Kristine Ferris, also of Agriculture Branch. A local farmer was contracted for the work. Field work was completed by staff from both Agriculture Branch (Kristine Ferris, Dillon Vickerman, Jonathan Lucas, Randy Lamb, Brad Barton, Matt Larsen, Tisha Organ, Shannon Gladwin) and the YukonU Research Centre (Rachel Pugh, Daniel Jolkowski, Anna Smith). Microbiological samples were analyzed by Lori Phillips and Brent Sueradge with Agriculture and Agri-Food Canada. The report was reviewed by Erin McBryan and Meg MacKay, and edited by Jonathan Lucas of Agriculture Branch.

Executive Summary

Agricultural land expansion is of interest to the Yukon; however, much of the land in the Yukon with farming potential is currently forested. Conventional methods of land clearing involve clearing the above ground forest and large roots, burning the organic materials, and spreading the ash. This practice removes organics from the system, releases large amounts of greenhouse gases in a short period, and the ash is not of great nutritional benefit to future agricultural endeavors. In the interest of retaining and using the organics as a potentially beneficial soil amendment instead of burning it as waste, Yukon Government Agriculture Branch proposed to experiment with different clearing methods involving incorporation of the forest organics into the soil. Concerns over the decomposing wood chips in soil 'stealing' nitrogen (immobilization) from other growing plants was addressed in a literature review in 2017. The review concluded that nitrogen immobilization, while expected, may be a short-lived phenomenon as the more readily decomposable materials will do so in the first year, and the more resilient organics will decompose so slowly in our cold northern soils that they will have a negligible effect on the available soil nitrogen.

Funding was obtained through Agriculture and Agrifood Canada's Canadian Agricultural Partnership's Regional Collaborative Partnerships program to implement a field trial exploring two different methods of incorporating the cleared forest organic materials into newly established agricultural plots. The first method was to use a forestry mulcher and subsoiler to shred and churn the organics in place into the top layers of the soil. The second method was to collect and shred the woody organics into a pile, then top-spread approximately one-third of the shredded material every year of the trial after seeding. A third treatment of conventional clear and burn was used as a comparison. The study took place in the Murray Agricultural Subdivision of the Ibex Valley, Yukon. Initial clearing and mulching was completed in 2020. Four, 30mx120m plots of each of the three treatments were randomly assigned in a block design and planted with oats with a standard fertilizer blend in both 2021 and 2022. Soil from each plot was sampled at key times throughout the trial and analyzed for nutrients, general chemistry, microbiology, and texture. In-situ temperature and moisture monitors were installed in each plot, and yield sampling of each plot was done in the fall of each year. Equipment operators recorded their fuel use, and greenhouse gas emissions were calculated for each treatment.

Results suggest that nitrogen immobilization can be observed in the forestry mulched plots in both years of the trial as evidenced by lower yields, the appearance of poorer health in the plants (paler colour and smaller, thinner plants), and an absence of detectable plant-available nitrogen in the soils. The surface mulch treatment and the conventional treatment did not show significant differences in soil testing or yield. From a greenhouse gas emissions perspective, the conventional treatment emissions were two orders of magnitude higher than the two organics-incorporating treatments. Cost-wise, the conventional treatment was the least expensive, with the forestry mulching being somewhat higher, and the surface mulch treatment being the most expensive largely due to the costs of both initial chipping of the material and its respreading each year. Costs for the treatments are not considered fixed however and are included only as comparative data for the procedure taking place at that time.

In future years, the site will continue to be used for ongoing research regarding differences between the plots for both soil chemistry, microbiology and crop yields. Some crops new to the Yukon may be included to demonstrate utility for the Yukon agriculture industry. If future trials of these techniques are undertaken, it would be of benefit to test what level of supplemental nitrogen would offset the observed nitrogen immobilization effects.

Table of Contents

1.0 Introduction

1.1 Study Context

The Yukon climate presents many challenges for agricultural production. While summers have additional hours of daylight which is generally beneficial to plant growth, our northern inland location also features a short growing season, year-round frost potential with late spring and early fall frost dates, low annual precipitation, and cold, poorly developed soils tending to be low in organic matter and available nitrogen (N). Nonetheless, the Yukon also has an active and innovative agricultural sector and an interest in increasing the land available for production. Given that much of the land in the Yukon with farming potential is currently forested, conversion of these lands requires the removal of trees and other forest biomass to prepare the land for agricultural planting. Conventional conversion methods are to cut down the above-ground biomass salvaging useable timber as appropriate, disk and rake the roots, pile the organic materials to dry out, then burn them outside of wildfire season and spread the resulting ash on the land. The spread ash has low nutrient value with an approximate NPK ratio of 0-1-3 and a high pH (University of Maine Cooperative Extension, 2006); it is of limited benefit in Yukon field soils where natural levels of N are very low and pH trends towards alkaline.

Considering Yukon Government commitments to reduce greenhouse gas (GHG) emissions in the territory (Government of Yukon, 2020), burning forests during conversion to agricultural land is an undesirable source of GHG release. The annual GHG emissions of the Yukon in 2021 was 700,000t (Environment and Climate Change Canada, 2023). This figure does not include GHG emissions from land clearing as GHG emissions from land clearing is presently considered carbon neutral in Canada. The true carbon neutrality of wood and biomass burning is a subject of some disagreement (Cornwall, 2017) and significant GHG release from soil carbon stocks during land use change is an ongoing area of research (e.g. (Mäkipää et al., 2023)). In the context of agricultural land clearing, there is no intention of the forest biomass regrowing and thus reabsorbing the carbon over time, and carbon stored in or released from agricultural lands during clearing or subsequent production will vary greatly depending on the cultivation methods and crops grown.

CO_2 is the main GHG released from burning forest biomass. CO_2 released from wood burning can be estimated as 1.8kg of CO_2 per kg of wood burned (Aurell, Gullett, Tabor, & Yonker, 2017). Yukon Government estimates that each hectare of Yukon forest holds, on average, 200t of woody material (Government of Yukon, Agriculture Branch, 2018) (Loeks & Trans North Consulting, 2021). Consequently, each hectare cleared conventionally releases 360t of CO_2[1]. For comparison, a passenger vehicle with 8L/100km fuel efficiency would drive approximately 1.9 million km (i.e. driving from Vancouver to Halifax 308 times) to release 360t of CO_2[2]. Alternately, this distance can be considered as driving to the moon five times, to release the same amount of GHG as from burning 1 ha. of Yukon woodland.

As natural Yukon soils tend to be low in organic matter, and surface and shallow subsurface biomass is removed as waste during conventional land conversion, it was questioned if the removed biomass could be returned to the land as useful organic matter. The potential for using wood chips as a soil amendment in Yukon soils was initially investigated in 2017 through a literature review by Krystal Isbister of FloraTek Consulting. The review identified the potential risk of nitrogen immobilization in the soil via wood decomposition processes but also suggested that the slow decomposition rates in cold northern soils may reduce the risk of severe immobilization effects after the first year (Isbister, 2017).

Agriculture Branch of the Government of Yukon, Department of Energy, Mines, and Resources obtained funding support from Agriculture and Agrifood Canada through the Canadian Agricultural Partnerships Fund in collaboration with Government of North West Territories to implement a three-year[3] field trial exploring two different methods of incorporating the cleared forest organic materials into the newly

[1] This is an estimate which illustrates the scale of the emissions being generated; precise figures would be dependent on the volume, tree/shrub types, wet/dry conditions, completeness of burning, etc.
[2] CO2 emission from passenger vehicle calculated with http://www.zeroghg.ca/carbon_calculators.html
[3] Due to delays with the clearing activities, only a small test strip of oats was planted late in the first summer (2020) to test germination, with full oat crops planted in years two (2021) and three (2022) for this trial.

established agricultural plots with comparison to a conventional clear and burn treatment. Of the two organic incorporation methods, the first (FM Forestry Mulch) was to use a forestry mulcher which is driven through the forest, pushing down the trees and shrubs, shredding and chipping them, followed by a subsoiler which churns the shredded wood into the top layers of the soil. The second method (SM Surface Mulch) was to collect and shred the woody organics into a pile, then top-spread approximately one-third of the shredded material every year of the trial after seeding. These treatments were compared with a conventional clear and burn treatment as a control (C Conventional). The trial ran from spring 2020 through winter 2022-23, with the Yukon University Research Centre contracted to manage data and report on the trial's findings.

1.2 Study Area

The study took place on 4.32ha of forested, newly released agricultural land in the Murray Agricultural Subdivision in the Ibex Valley, Yukon (NW corner of plot area 60°51'51.54"N, 135°40'17.24"W).

FIGURE 1 LOCATION OF STUDY PLOTS, YUKON, CANADA, IMAGERY GOOGLE EARTH

The area is 360m (east-west) by 120m (north-south); twelve side by side (east to west) plots were established measuring 30m by 120m each (see figure 2, next page).

The land is relatively flat with minor high and low points, and the foot of a very small hill creates a rise at the north end of two of the plots.

FIGURE 2 LAYOUT OF STUDY PLOTS, IMAGERY GOOGLE EARTH

The area was previously undeveloped, although affected by a wildfire in 1958[4]. The dominant tree species is small-diameter aspen (consistent with post-fire secondary succession in an early intermediate phase) with willow, mixed shrubs, and ground cover, and some smaller conifers (white spruce, lodgepole pine).

PHOTO 1 ORIGINAL FOREST COVER PRIOR TO CONVERSION IN BACKGROUND WITH THE NEWLY MULCHED FM TREATMENT IN THE FOREGROUND, JULY 2020

[4] YG Historical Wildfire Map, file available from https://yukon.ca/en/emergencies-and-safety/wildfires/view-yukon-wildfire-maps

Numerous decaying deadfall trees lie on the ground, presumably killed by the wildfire event or other natural processes. Occasional larger, mature trees (aspen, spruce, pine) suggest some trees may have survived the fire or were established very early after the fire. The choice of site was restricted by availability. Work with conifer-dominant mixed forest is expected to be the subject of a continuation of this project.

2.0 Treatments and Study Design

The three treatments in this study were:

- FM forestry mulching where a forestry mulcher was driven over the plot area to knock down and shred the vegetation. A subsoiler was then used to shred roots and mix all the woody material into the top 30cm of soil.

- SM surface mulch spreading where the vegetation was cleared off the plot with a bulldozer, then shredded with a horizontal grinder/chipper and piled at the edge of the plot. Approximately one third of the shredded material was spread as surface mulch each year immediately post seeding, and in succeeding years the previous year's surface treatment was turned into the soil with disking.

- C the conventional bulldoze clear, windrow, and burn treatment.

Both SM and C treatments later required significant forest root removal through disking, root raking into root windrows, and loading and trucking off those plots.

Four plots of each treatment were randomly assigned in a block design (i.e. the 12 plots were split into four, three-plot sections, and the three plots within each section were each randomly assigned one of the three treatments. See Fig 2 on pg 4). Following a common field preparation practice where oats are grown for at least two seasons and tilled into the soil as green manure to prepare a newly established field, the plots were planted with oats each year (110lb/ac broadcast seeded in

2021, 108lb/ac drilled 1.5" in 2022) and a standard fertilizer blend was applied (175lb/ac 30-8-8-4 in 2021 and 158lb/ac 30-8-8-4 in 2022).

PHOTO 2 EXAMPLE OF SOIL SURFACE AFTER TREATMENT, PHOTO CREDIT DILLON VICKERMAN

The study's original design was for clearing and crop planting to occur in the first year, with two subsequent years of crop planting to follow. The plot preparation and treatments for the first field season were affected by various delays as summer 2020 was after the March 2020 World Health Organization declaration of COVID as a pandemic and Public Health Emergency of International Concern. This significantly and negatively influenced the ability of field workers and equipment operators to travel freely.

The forestry mulching and subsoiling were completed in July 2020 for the FM treatment and a small strip of oats was sown a few days after the subsoiling on plot FM4 to demonstrate the speed of land conversion using this method. Conventional and SM clearing (which likewise required bulldozing) did not take place till winter 2020-21 as this method is most effective when the ground is frozen. SM organic materials were bulldozed off those plots in December 2020 and shredded in March 2021; C organic materials were bulldozed into piles in Dec 2020. Burning of the windrows for the conventional treatment was not completed in winter 2020/21 due to wetness within the piles (from moisture within the fresh material and then winter snow accumulation) during the Oct-April open burn period. The piled windrows remained in place during the summer of 2021, with the oats sown around them and were finally burnt over winter 2021-22.

PHOTO 3 MULCH PILES READY FOR SPREADING AT THE END OF SM PLOTS, WITH WINDROWS NOT YET BURNED IN C PLOTS, JUNE 2021.

The first complete plot seeding of oats was completed in the summer of 2021. The direction given to the farmer was to sow the seed using their usual technique, so they used a broadcast seeder. Seed was broadcast with a fertilizer mix and harrowed. Subsequent seed germination in the FM treatment plots in 2021 was patchy and the plants showed evidence of poor nutrition (pale colour, reduced plant size and stalk thickness). Because there appeared to be a problem with the germination and not just the plant growth, it was theorized that the aeration of the soil during the mulching/subsoiling may have resulted in “fluffy” soil which reduced seed contact with the soil and negatively affected the germination and growth of the crop. Although this could not be confirmed without further specific study, it was considered a very reasonable possibility, and thus a seed drill and soil compression were used in 2022. Allelopathy, where biochemical compounds within the mulched material inhibit the growth of other plants, was also considered, but a scan of literature on the subject did not show strong support, and thus it is believed that reduced seed/soil contact is the likelier cause. No irrigation is available on site, so the crop only received ambient precipitation. Excepting elk and bison found grazing on the crop late in the season, no pest problems were observed. Pest management methods were neither required nor applied.

3.0 Sampling and Methods

Soil sampling for nutrients, microbiology, and general chemistry was undertaken for each plot several times throughout the study. The timing of the soil sampling reflected a change in the site activities as follows: June/July 2020 – pre-clearing; May 2021 – pre-planting; September 2021 – end of season; July 2022 – pre-planting; September 2022 – end of season. For soil chemistry, the conventional treatment plots were excluded from the May 2021 sampling based on the reasoning that the windrow burning had not been completed, and thus no treatment/activity had occurred since the previous year's sampling[5]. To obtain one composite sample from each plot, the field team walked the length of the plot in a zig-zag pattern, taking one soil core of approximately 0-20cm depth every five paces for a total of 15-20 soil cores. The soil cores were put in a bucket, thoroughly mixed with a trowel to break up clumps and coarsely homogenize the material, then transferred into a sample bag with any excess discarded. Soil samples were sent to Element Lab in Edmonton, AB, where they were further ground and homogenized before testing for soil nutrients, general chemistry, and texture.

During the summer of 2021, an opportunity arose to have the microbiology of the soil plots analyzed by scientists at Agriculture and Agri-Food Canada's Harrow Research and Development Centre, Ontario. Soil samples from each plot and one additional sample from the adjacent forest land were taken in July 2021 and September 2021 and placed immediately in a cooler for transport to the Yukon University Research Centre Lab where they were stored in a freezer at -80C. Samples were later shipped in an ice-packed cooler to Harrow, ON for processing and extraction and then sent on to Genome Quebec in Montreal, QC, for sequencing work. Samples from the twelve plots and an additional four forest locations (north, south, east, and west of the research plots) were taken during the July and September 2022 sampling trips and sent to Harrow for analysis. Results of the microbiological analysis are briefly summarized in the results section and are further explained in Appendix C. This work resulted in an abstract paper published

[5] This is now believed to be an error, if a largely inconsequential one, as the soil chemistry (in particular nitrogen species and organic matter) may have evolved over the 10 months between sampling events due to the removal of surface cover and changing soil microbiome, and ongoing microbial processes.

at the Canadian Society of Soil Science conference, 2023 (Seuradge et al., 2023: *Northern boreal forest conversion to agricultural landscapes alters soil microbial carbon and nitrogen cycling potential.*).

Two soil temperature sensors (Onset HOBO TidbiT v2 Temperature Data Logger) and one soil moisture sensor (Onset 10HS Soil Moisture Smart Sensor) were installed in each plot and retrieved at the end of the season. For the temperature, two tidbits per plot were buried approximately 10cm below the surface, one in the north half and one in the south half of each plot. For the moisture probes, an approximately 10cm deep hole was dug into the soil, a small amount of water was trickled into the hole, moistening the surrounding soil to improve initial contact for the probe, then the probe was placed in the hole, and the hole backfilled. A HOBO data logger was zip-tied to a wooden stake and positioned between every two plots with two adjacent plot moisture monitors connected to one logger. Loggers and instruments were removed in the fall, and data was downloaded with Onset HOBOware software and then exported to Excel.

PHOTO 4 HOBO LOGGER CONNECTED TO MOISTURE SENSORS

Yield estimates were carried out by a field team using randomly generated number coordinates representing the dimensions of the plot in metres excluding the outer 2m along the plot borders to select 10, 50cmx50cm squares. All vegetation (oats) within each square was cut approximately 5cm from the base of the stalks, placed in labelled paper bags, and later dried and weighed. A visual estimate of vegetation coverage was made for each square, given the patchy germination of seed and plant establishment in 2021. The trial area was unfenced, and local elk and bison were found to be grazing within the plots; however, this grazing was limited in area

PHOTO 5 YIELD ESTIMATE SAMPLE COLLECTION

at the time of sampling. Where a yield estimate square was to fall in a spot that had been grazed, another area nearby was selected in its place that appeared to have roughly the same vegetation coverage as the stalks left behind by the grazing animals. Yield results were analyzed statistically in Excel.

4.0 Results

The primary data for comparison between treatments in this study were yield, soil available nitrogen, and soil organic matter. Additional data collected were soil moisture, soil temperature, and soil microbiology, as were field observations of plant health and estimates of % plant cover as an indicator of germination success and influence on yield.

4.1 Soil Available Nitrogen

TABLE 1 SOIL AVAILABLE NITROGEN (PPM)

	C (avg)	SM (avg)	FM (avg)
Jul-20	n/d	n/d	n/d
May-21	-	n/d	n/d
Sept-21	3	n/d	n/d
Jul-22	7.25	7	n/d
Sep-22	4.75	n/d	n/d

n/d = below limit of detection i.e. <2ppm

Soil available nitrogen was below the detection limit of 2 ppm for most of the samples. As such, presence/absence, and the quantity measured when present are considered the appropriate way to evaluate the soil available nitrogen relative to each treatment rather than any statistical comparison. For the pre-clearing soils, none of the plots had detectable available nitrogen. Soil samples taken from the adjacent forest in July 2022 and September 2022 (at the request of the microbiology team and not shown here) also did not have detectable levels of available nitrogen. It can be assumed that this presents a baseline for the forest soils in the area, and available nitrogen levels in the C and SM plots in later years are influenced by cultivation activities such as application of inorganic fertilizer, disking-in of crops, incorporation of woody material etc.

4.2 Soil Organic Matter

TABLE 2 SOIL ORGANIC MATTER (%)

	C (all)	SM (all)	FM (all)
Jul-20	5.475	5.275	5.075
May-21	-	4.775	4.9
Sept-21	5.625	5	5.125
Jul-22	4.75	5.925	4.925
Sep-22	6.425	7.8	5.425

Soil organic matter was analyzed for differences over time within treatments and differences between treatments. The July 2020 results represent the plots prior to disturbance, whereas the temporal difference of interest for soil building is the May 2021 post-clearing/pre-planting sampling event and the final Sept 2022 harvest sampling event. In this case, it was an error to not sample the C treatment plots in May 2021, as the disturbance caused by the clearing was not captured as potentially differing from the undisturbed plots. Paired t-tests were done for: C at July 2020 and Sept 2022, and Sept 2021 and Sept 2022; SM at July 2020 and Sept 2022, and May 2021 and Sept 2022; and FM at July 2020 and Sept 2022, and May 2021 and Sept 2022. Both SM tests were found to be significant ($p < 0.05$), with OM being higher in Sept 2022 than at the previous times. No significant difference was found between sampling events for C or FM. A one-way analysis of variance (ANOVA) was performed on the three treatments for both July 2020 and for Sept 2022. No significant difference was found between the treatments at those times ($p < 0.05$).

4.3 Crop Yield

With only two years of data and varying conditions from year to year, no comparison between years has been made, but rather the differences between treatments for each year is examined. Treatments were analyzed in Excel for statistical significance between groups using a one-way ANOVA, followed by post hoc Tukey's HSD tests to determine which pairs of treatments were significantly different.

2021

TABLE 3 CROP YIELD 2021, T/HA LEFT, T/AC RIGHT

Yield 2021 (t/ha)	C	SM	FM
1	2.88	3.44	2.22
2	2.76	2.17	1.87
3	2.94	2.18	1.41
4	2.55	3.41	0.93
average	2.78	2.80	1.61

Yield 2021 (t/ac)	C	SM	FM
1	1.17	1.39	0.90
2	1.12	0.88	0.76
3	1.19	0.88	0.57
4	1.03	1.38	0.38
average	1.13	1.13	0.65

The one-way ANOVA revealed that there was a statistically significant difference in 2021 mean plot yield between at least two groups ($F(2, 9) = [6.487]$, $p=0.018$). Tukey's HSD test for multiple comparisons found that the plot yield's mean value significantly differed between C and FM and between SM and FM at $p < 0.05$ in 2021. There was no statistical difference in yield between C and SM in 2021.

2022

TABLE 4 CROP YIELD 2022, T/HA LEFT, T/AC RIGHT

Yield 2022 (t/ha)	C	SM	FM
1	**5.65**	2.69	1.35
2	3.12	**3.63**	1.73
3	3.48	**4.36**	1.86
4	3.55	2.37	**4.05**
average	3.95	3.26	2.25

Yield 2022 (t/ac)	C	SM	FM
1	**2.29**	1.09	0.55
2	1.26	**1.47**	0.70
3	1.41	**1.76**	0.75
4	1.44	0.96	**1.64**
average	1.60	1.32	0.91

[bold = suspect high value]

TABLE 5 CROP YIELD 2022, T/HA LEFT, T/AC RIGHT, ADJUSTED TO REMOVE HIGH VALUES

Yield 2022 (t/ha)	C	SM	FM
1	3.12	2.69	1.35
2	3.48	**3.63**	1.73
3	3.55	2.37	1.86
average	3.39	2.90	1.64

Yield 2022 (t/ac)	C	SM	FM
1	1.26	1.09	0.55
2	1.41	**1.47**	0.70
3	1.44	0.96	0.75
average	1.37	1.17	0.67

The one-way ANOVA revealed no statistically significant difference in 2022 mean plot yield ($p < 0.05$).

Reviewing the data, it was noticed that one sample for the C and one sample for the FM treatment were noticeably much higher than the others of the same treatment, and two SM values were noticeably higher than the other two values. The 2021 yield sampling was done by one two-member team, whereas the 2022 yield sampling was completed by three two-member teams. When the field sheets were compared to the high data values, it was found that all the high data values (one C, one FM, 2 SM) were sampled by the same field team. It is believed that the high data points may be a result of unintended positive sample bias by this field team and are not reliable representations of the treatment yield. If the highest values for each treatment are removed from the data set (the second highest value was retained for SM to maintain three samples for statistical analysis of the treatment), the ANOVA then reveals a significant difference in the 2022 mean plot yields ($F(2, 6) = [13.152]$, $p=0.006$). Tukey's HSD test for multiple comparisons found that the mean value of plot yield was significantly different between C and FM and between SM and FM at $p < 0.05$. No statistical difference was found in yield between C and SM in 2022, although with the retention of the second highest yield value in the SM treatment, this result may be skewed to higher SM values, and thus this result should be considered unreliable. It is recognized that excluding the high values could be criticized as 'cherry-picking' data, but it is believed to be defensible in this case. Yields from these plots will continue to be recorded in future years which will contribute to a better understanding of the treatment effect on yield over time.

4.4 Soil Temperature

Soil temperature data was collected from two sensors in each plot, resulting in eight temperature readings per time interval per treatment. A time series of average temperatures was created for the three treatments.

2021

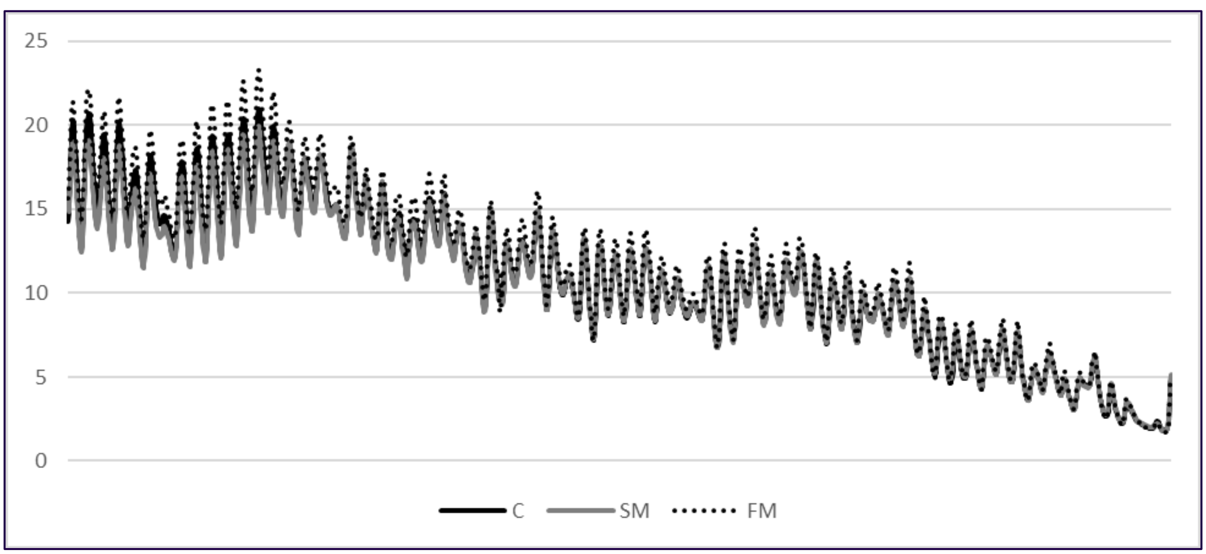

CHART 1 SOIL TEMPERATURE JULY 20, 2021, THROUGH SEPT 29, 2021 (DEGREES C)

Sensor SM4-North did not record any data and thus was excluded from pooled SM data. Sensors were installed in the FM and C plots in early July. The SM sensors were not installed until July 20, 2021, as the mulch had not been applied when the other sensors were installed, and then there was a delay in getting the SM sensors in place. For analysis, the data was trimmed to exclude the record prior to July 20, 2021, and after the sensors were removed on September 29, 2021. For the in-field period observed, results show FM plots having consistently higher temperatures than the other two treatments until about mid-September, when the difference becomes minimal and then negligible by the end of the month when the sensors were removed. The C treatment temperatures were consistently higher than the SM treatment until early August, when they became close to the same.

These temperature differences may initially reflect a slight cooling effect from the surface mulch application armoring the soil surface which is then minimized when the plant growth starts to provide temperature moderation. FM had poorer germination in 2021 compared to the other two treatments, so the soil temperatures may be receiving more solar radiation to the soil surface with less protection from plants. It should be noted that these differences, although consistent, are also minor and not more than three degrees Celsius at the extreme.

2022

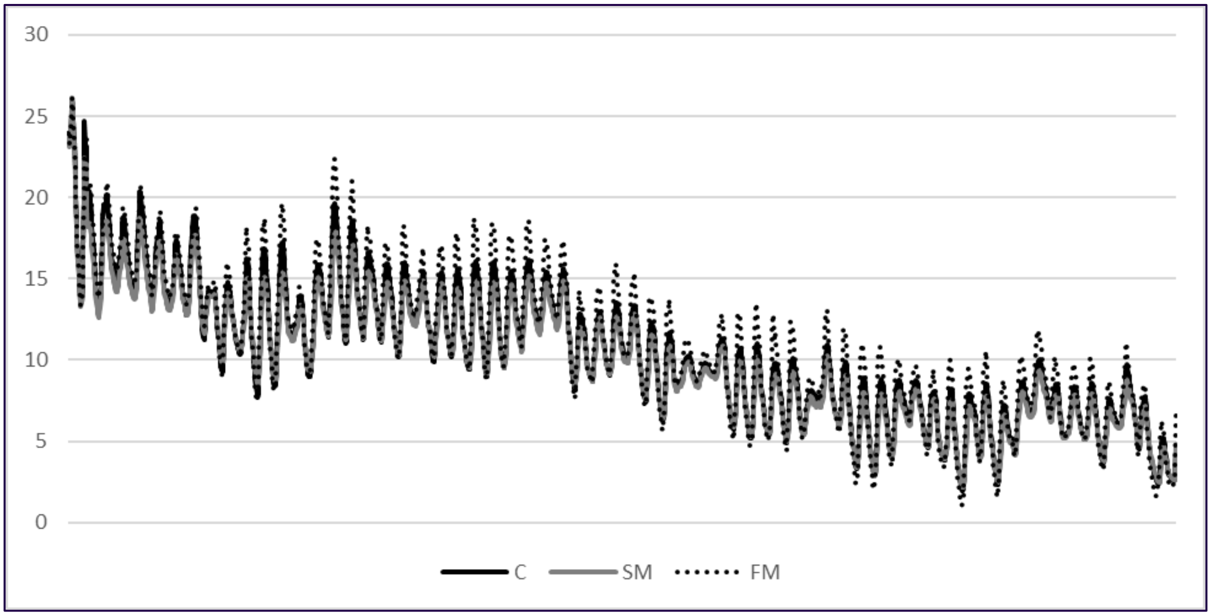

CHART 2 SOIL TEMPERATURE JULY 28, 2022, THROUGH SEPT 29, 2022 (DEGREES C)

In 2022, results show a relatively consistent trend of the FM treatment reaching the highest daily soil temperatures, and often the lowest daily temperatures, although this is less consistent and is minimized towards the end of the growing season. This differs from the previous year, where FM reached the highest daily temperatures but not the lowest. The SM treatment shows the most limited range of daily temperature, and the C treatment is in between, generally reaching a similar or greater low than SM and a greater high than SM. As in the previous year, this could be interpreted as the SM treatment armoring the soil surface and providing a minor cooling effect. The larger temperature swings with the FM treatment could be an effect of the lesser crop growth, although the trend in 2022 stays apparent into late September when the plant growth and coverage is at its maximum. The temperature differences between FM and C appear least at the start of the season when plants are small and produce less shade and transpiration.

4.5 Soil Moisture

2021

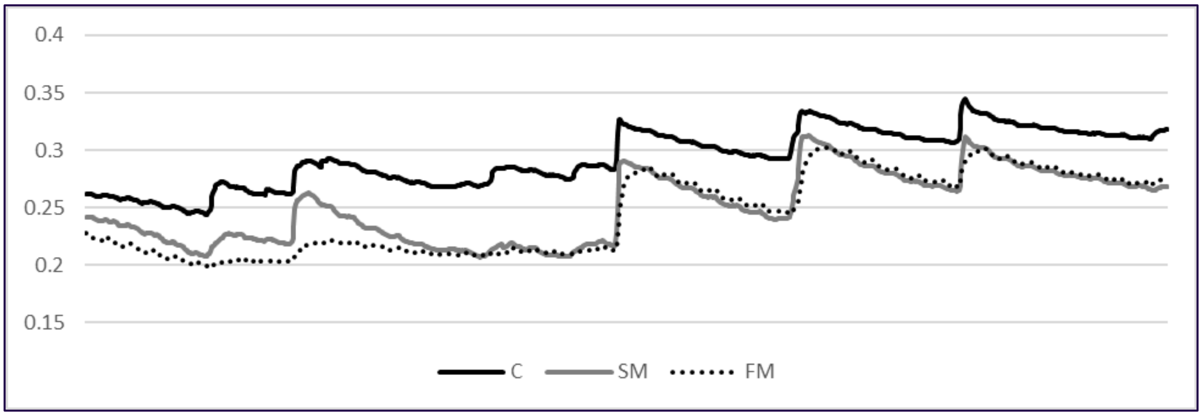

CHART 3 SOIL MOISTURE JULY 28, 2021, THROUGH SEPT 14, 2021 (M^3/M^3). JULY 13-27 NOT SHOWN DUE TO LACK OF PRECIPITATION EVENTS

Although the soil moisture sensors could be relied upon to indicate when a precipitation event occurred and show the general moisture regime, several of the sensors failed at some point during the season (SM4, SM1, SM3, FM4). For the stretch of time that all sensors appear functional (July 13, 2021, through September 14, 2021, excluding C2 and SM2 for which the shared HOBO logger did not record any data), the data were combined to create treatment averages and line graphs to observe any trends. Treatment C had a consistently higher moisture level compared to the SM and FM treatments, which were more similar. The C and SM treatments showed sharper peaks at precipitation events, and the FM treatments appeared to lose moisture more slowly after the peak of a precipitation event.

It should be noted that although the C plots were cleared, they were not yet disked in 2021 and thus the soil was not opened up as it was for the SM and FM treatments, however it would not be considered compacted. In contrast, the FM plots were deeply aerated and ‘fluffed up’ by the subsoiling process and also contained the woody debris which is presumed to be the reason for the gentler peaks in the FM treatment showing a slower release of moisture from the soil.

2022

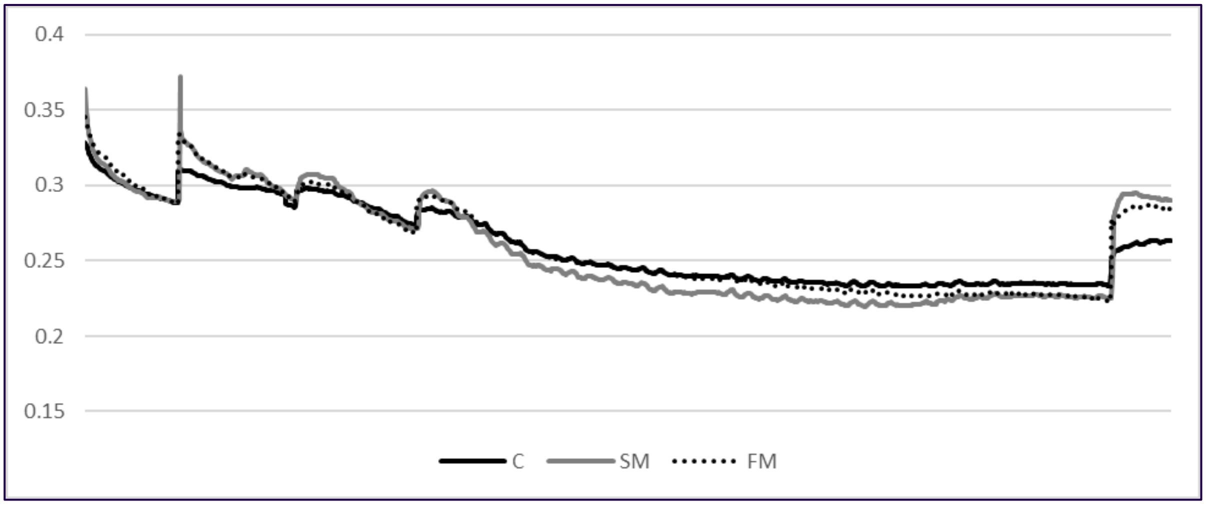

CHART 4 SOIL MOISTURE JULY 29, 2022, THROUGH SEPT 29, 2022 (M^3/M^3)

As in the previous year, in 2022, several of the sensors failed at some point during the season (FM2, SM2, SM4, C1). There may be a noticeable trend towards the FM treatment having the most moderate changes in moisture content, with SM generally showing the highest peak during a precipitation event and C showing the lower peak. This is indicative of the shredded woody material retaining moisture. The data are not considered particularly reliable nor explanatory, and it is believed that the individual sensors used may not be the correct tool for this measurement intended for comparison. Slightly differing soil texture may also influence each plot's moisture content. This monitoring should continue for future years, perhaps with different equipment, and the data should be assessed against the previous years to see if any reliable trend can be seen.

4.6 Soil Microbiology

A summary of the soil microbial analysis is provided by Lori Phillips, Ph.D., a scientist with the Harrow Research and Development Centre, Agriculture and Agri-Food Canada:

> "After land clearing both bacterial and fungal communities rapidly shift away from the baseline community structure found in forest soils. In undisturbed forest soils the fungal phyla Basidiomycota and Ascomycota each account for approximately 48% of all fungi. After land conversion, Basidiomycota groups decrease to approx. 10% of the community, while Ascomycota increase to over 80%. Although this is [a] common difference between forest and agricultural soils, this fundamental shift occurred within a very short period of time. This shift in fungal dominance will alter everything from the rate at which new and old carbon will be cycled to the control of soil-borne pathogens. For example, there was up to an 800% increase in the abundance of the Ascomycota *Trichoderma*, which is a known plant growth promoting fungi that also functions as [a] biocontrol agent. Shifts in bacterial communities were more nuanced, with larger changes seen in specific organisms that cycle nutrients. For example, bacteria involved in nitrification (the transformation of fertilizer or ammonia-N to plant-available N) increased by up to 1400 % (i.e. from almost non-detectable in the forest soils to highly abundant in the agricultural soils. All of these shifts in bacterial and fungal communities, which ultimately control carbon and nitrogen cycling in soil, have implications for the health and sustainability of the agricultural system."

4.7 Field Observations

During the fall yield sampling, field teams also recorded observations on the apparent germination success (% coverage estimate) and plant health. These observations were not particularly rigorous in that no colour chart, measurements, or particular methodology were applied for consistency; nonetheless, the observations are considered pertinent and reasonable for mention in the reporting as complementary information. Observations in 2021 were recorded by one two-person team and thus had greater consistency in observation. The average coverage estimate for FM treatments was 19.9% (+/- 17.4), SM was 36.3% (+/- 17.6), and C was 37.9% (+/-21.2).

PHOTO 6 AERIAL VIEW OF THE STUDY PLOTS LOOKING WEST, SEPT 2021, PHOTO CREDIT: RIC J. HOROBIN

These values are not intended to reflect true seed germination rates for each treatment but rather the approximate amount of vegetative cover. The high standard deviation shows the variability amongst the yield harvest sub plots.

Visual observations of FM tended to see more descriptors such as yellow, yellow/purple, pale green, green, short, poor growth, and skinny. SM had descriptors of green, green to pale green, with occasional yellow or dark green, while C was described most often as dark green or green, with occasional notations of yellow or poor growth. These descriptors give a picture of generally healthier and more vigorous plants in the C and SM treatments, with the FM treatment having both lower germination rates and signs of nutrient deficiencies. This is consistent with the premise that decomposition of the wood by micro-organisms is utilizing soil nutrients and added fertilizer more efficiently and/or rapidly than seedling roots.

PHOTO 7 FM TREATMENT: LEFT SIDE EARLY AUGUST 2021, POOR GERMINATION, PALE COLOUR; RIGHT SIDE LATE SEPT 2022, IMPROVED GERMINATION, SMALL PLANTS, PALE COLOUR. LEFT PHOTO CREDIT KRISTINE FERRIS.

PHOTO 8 VIEW LOOKING NORTH SEPT 2022, SM2 TO THE LEFT OF THE MARKER, C3 TO THE RIGHT

Three two-person teams completed observations in 2022, each covering four plots. Germination rates were generally quite good in 2022, which could be easily seen given the consistent planting pattern of the seed drill. However, one of the teams had vastly different coverage estimates, with coverage estimates generally in the 80-100% range. The other two teams had coverage estimates generally below 50%. It is believed that one team estimated the germination success based on the vegetation deriving from the seed drill pattern while the other teams estimated the vegetative coverage. The visual observations are perhaps more reliable and not unexpected, with the FM treatments more frequently described as pale green, SM as pale green or green, and C as green or dark green. Although these observational records have inconsistent observers, it is still considered good documentation to have, with the recommendation that any future recording of such details be based on a common reference and more consistency with the observers. Considering the 2021 and 2022 observations together, the FM treatment shows evidence of reduced nitrogen stealing effects from the wood decomposition in 2022.

One interesting observation from 2022, which was not observed in 2021, was a lack of seed head development in the SM plots. This was consistent through all four SM plots, and not the other treatments which showed fairly consistent seed heads on the plants, while the SM plots had few. It is unknown what might cause this phenomenon, and it will be interesting to look for in future years.

4.8 GHG Emissions and Financial Costs

GHG release and financial cost data were recorded and calculated by the Project Lead: Jonathan Lucas, Agricultural Lands Manager with YG's Agriculture Branch. Costs do not include mobilization and demobilization nor delivery costs to the site as this is highly variable. Thus, the stated costs are for the work that occurred on the farm as if all implements were available at the farm. Diesel use by machinery was recorded by the operators. It is assumed that an average hectare of Yukon forest produces 200t of wood (from a YG Forestry Branch estimate) and that 1t of wood releases 1.8t of CO_2 when burnt. A diesel to GHG conversion of 2.681kgGHG/L diesel was used[6].

TABLE 6 SUMMARY OF CLEARING COSTS BY METHOD. DETAILED TABLE IN APPENDIX.

Clearing method	Area (ac)	Time (h)	Diesel use (L)	Waste organics incorporated in soil (t)	GHG release from fuel (t)	GHG release from wood burning (t)	GHG release (t)	Development Costs ($)
Forestry Mulch	3.7	57.5	2120.27	74.1	5.68	0	5.68	17035.78
Surface Mulch	3.7	105.49	2008.87	74.1	5.39	0	5.39	28729.62
Conventional	3.7	69.32	1037.87	0	2.78	485.83	488.61	13127.12

TABLE 7 DEVELOPMENT COSTS PER ACRE (CDN)

Treatment	Cost per acre	Increase over Conventional/acre	
Forestry Mulch	$4604.26	$1056.39	+30%
Surface Mulch	$7764.76	$4216.89	+119%
Conventional	$3547.87	-	-

TABLE 8 GHG RELEASES

Treatment	t GHG/acre	t increase over Surface Mulch/acre	
Forestry Mulch	1.54	0.08	+5.5%
Surface Mulch	1.46	-	-
Conventional	132.06	130.6	+8954.2%

The differences in costs and GHG emissions are quite striking. While having the lowest GHG release, the SM treatment required the most hours of labour as well as having a high hourly cost for the grinder and operator. Surface spreading the mulch and re-piling the remainder was also time-consuming. If the mulch were applied all at once, the costs for this treatment would be reduced; however, the major cost is the grinding of the material and the root raking in later years. The

[6] source: Government of Canada National Inventory Report 1990-2021: Greenhouse Gas Sources and Sinks in Canada, Part 2, Table A6.1-5, "Emission Factors for Refined Petroleum Products" accessed through https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/emission-factors-reference-values.html#toc4.

major cost of the FM treatment is in the mulching and subsoiling, which was only marginally less than the clearing and grinding for the SM treatment (13.5K for FM, 15K for SM). FM did not require much root raking in 2022. By comparison, the C treatment cost for clearing and burning was substantially less at 3.5K, but then also required time and equipment for root raking in 2022. Although not accounted for here, the costs of equipment mobilization/demobilization (or moving equipment to and from a work site) will also have a budgetary impact on any future project considering these techniques.

For GHG emissions, the CO_2 release for the SM and FM treatments, respectively, were 5.39t and 5.68t, all from fuel use, while the C treatment was 488.6t (2.8t from fuel and 485.8t from wood burning). It should be acknowledged that the buried woody material in FM and SM will also release CO_2 (as not all C may be sequestered in soil organic carbon) as it decomposes; however, decomposition is expected to be a very slow process in cold, dry northern soils and will thus not compare to the immediate release from burning.

5.0 Synthesis

The premise of this study is to explore the estimated GHG release from three different land conversion treatments while comparing the crop productivity, soil development, and economics of each treatment with an eye for potential nitrogen-stealing by the decomposition of woody materials in the FM and SM treatments and any differences in organic matter, soil temperature, and soil moisture between the treatments and any consequences for crop production.

Although soil OM appears to show change over time, only SM had a statistically significant difference between the original soil OM level and that was at the end of the study. There was no significant difference in OM between the treatments, which is not unexpected with only two years of soil development.

Trends in soil moisture and soil temperature were not particularly clear. They were likely more affected by plant growth/cover (FM had the poorest growth/coverage and the highest soil temperatures) and minor differences in soil texture than soil differences between the treatments at this point. However, a soil cooling trend could be supported with the SM treatment attributable to the physical surface cover, and the FM treatment showed some evidence of moisture holding by the incorporated woody materials. It is important to note that this study covers only two growing seasons, and the soil will continue to develop over time. The continued degradation of the woody materials incorporated in the SM and FM treatments may show effects in the longer term that are not yet revealed.

Study results suggest that available nitrogen applied from fertilizer is being consumed by crop growth as well as wood decomposition processes. Thus, less nitrogen is available to the growing plants in the SM and FM treatments. This is evidenced both by the consistently undetectable levels of available N in the FM treatment, as well as the mostly undetectable levels in the SM treatment, with the sub-soil wood in FM being more demanding than the surface-spread mulch in SM. This is also reflected in crop productivity and health, with the FM treatment showing statistically lower yield each year and observationally smaller, paler plants. The 2021 application of surface mulch would have been incorporated into the soil when the oats were disked-in prior to the 2022 planting, so both the FM and SM treatments in the second year have sub-surface woody material, although substantially less in the SM treatments as only a third of the above-ground woody material was incorporated, and the roots were raked out and removed. Interestingly, the available N appears to increase over the winter, given its higher levels for C and SM in the July 2022 sampling (samples taken a few days before fertilizer was added) compared to the October 2021 and September 2022 results. Microbial processes are known to continue over winter under the snowpack down to a temperature around -5C (Brooks & Williams, 1999), (Blankinship & Hart, 2012), so the increase in available N could be attributed to those processes. Subsurface temperature data for a nearby Ibex Valley location over winter 2019/20 shared by YukonU's Permafrost and Geoscience Program (Calmels & Roy, personal communication) show temperatures at 25cm mostly below -5C from November through March under the influence from ambient surface temperature. Microbial activity is therefore assumed to continue for a month after our latest sampling at the end of September and resume in April. Another possibility is that the fertilizer applied with the seeding each year is not fully dissolved during the growing season, and further dissolution occurs with the wet soil conditions of spring melt; however, if that were solely the case, it might be expected to show detectable N in the July 22 FM results also.

Fertilizer is a considerable expense to farmers; further understanding of the fate of nitrogen applications and natural nitrogen cycling may be of interest with the potential to minimize application needs and optimize the timing of the application. Of the other soil macronutrients and micronutrients (displayed in Appendix A), the overall soil characteristics tend to be deficient to marginal in boron and zinc; however, those low levels are seen across the treatments and thus aren't believed to be significant contributors to differences seen between treatments at this time.

As has previously been noted, the seeding method (broadcast) in 2021 may have contributed to poor germination and lesser plant health for the FM treatment that year, and there did appear to be an improvement in the germination and plant health for FM in 2022 compared to 2021. However, it is difficult to compare between years as environmental factors affecting plant growth differ from year to year. In the literature review produced by Isbister (2017), it was suggested that the effects of nitrogen stealing may not be important after the first year due to the very slow rate of decomposition of the woody materials. In this field study, we appear to continue to see some detrimental effects in the second year, but those effects appear somewhat lessened (based on observations of plant health) and may continue to diminish in subsequent years. SM does have some woody material incorporated into the soil in 2022 yet does not show a significant yield difference to the C treatment, so perhaps there is a maximum level of woody material that can be incorporated into the soil before negative effects on plant growth are seen, or perhaps the most readily decomposable components of the material have been broken down over the period they spent on the surface and further decomposition occurs at a rate slow enough to limit the drawdown of N. However, SM did have the curious lack of seed head development in 2022, which, if it continues, would be undesirable in a cereal crop.

A short-term study such as this, although it reflects a realistic timeframe of two years of green-manure incorporation on newly converted lands, is insufficient to understand the differences between treatments over the long-term. In subsequent years, the decomposing sub-surface material could show a benefit to the organic matter and moisture retention within the soil, or it could continue to contribute to reductions in available N for plant growth. It is not known what level of additional fertilizer N compensates for the N used in wood decomposition in northern soils, certainly 36ppm at the conventional kg/ha rate is insufficient. The project lead has indicated that this will be a subject of further studies.

After two years, evidence from this study suggests that the conventional C treatment is monetarily less expensive than the organics-incorporating SM and FM methods, has a statistically significant higher yield than the subsoil FM treatment, and is observationally healthier in appearance than the SM and FM treatments. However, much of the costs are dependent on the cost of externally owned equipment and operators. If equipment is available locally, the mulching and subsoiling treatment becomes financially more attractive, and increased demand may reduce the cost of the grinder used for the SM treatment. From a GHG emissions perspective, even if the numbers in the calculations are rough estimates, the conventional treatment is two orders of magnitude higher than the organics-incorporating treatments.

This phase 1 study has been valuable in observing the initial differences between treatments, both in effects on the crop as well as the financial costs and GHGs emitted by the treatments. Phase 2 of this study started in 2023, with half of each plot continuing with a crop of oats and the other half seeded with forage beets. It will be interesting to observe the continued soil development at the site over the next few years, which will contribute to a stronger picture of the effects of the treatments in the longer term.

If it is considered desirable to continue experiments with subsoiling as a land conversion technique, it would be interesting to investigate if the productivity decrease seen for FM in this trial could be mitigated by increasing the amount of chemical fertilizer or other N input applied to the system (it is acknowledged that this is an added expense). If longer-term benefits from the subsoiling are seen in future years at this trial site, and additional N can be added in earlier years to reduce or eliminate the yield loss, this subsoiling method could prove to be a viable land conversion method with long-term soil benefits while vastly reducing the GHG emissions compared to conventional methods.

6.0 Commentary on project results and points of interest

(by Jonathan Lucas, Yukon Government Project Lead, September 2024)

6.1 Soil Temperature

Although the temperature differences are small between treatments, the mulch used for the SM treatment may be acting as a soil surface armor, reflecting some direct sunlight (heat) and maintaining a lower soil temperature after seeding, or at least slowing soil temperature gain. This may result in slightly later germination In contrast the slightly warmer soil temperatures of the FM treatment may encourage earlier germination, which is helpful in the Yukon's short growing season.

6.2 Costs

SM Surface Mulch

The SM treatment is considerably more expensive and time consuming than either of the other treatments, such that it probably becomes impractical on a field scale. Regarding nitrogen availability, annually adding 1/3 of the wood back on the surface, and then disking it to a depth of about 6" in the fall did not appear to produce the more obvious and immediate N stealing effects of the FM treatment.

FM Forestry Mulch

The $1000 cost per acre difference between the Conventional C and FM treatments approximates to the cost of the subsoiling activity of the FM treatment. Practical developments with mulching machinery in the Yukon as a result of this study indicate mulchers may churn up to 3" deep into stone free soils.

Most Yukon coniferous trees are shallow rooted with many lateral roots just below the soil surface. Mulching 3” into the soil may replace the need and cost for the subsoiling activity. This theory is being tested in 2024, in a follow-up Yukon land clearing project borrowing from the trash blanket techniques of sugar cane production. Liniger (2007) indicates that such techniques have been shown to improve soil structure, increase sub-surface biodiversity, and reduce surface erosion

6.3 Mulch use

In spring 2021 there was only one machine in the Yukon capable of undertaking this chipping/shredding work that the Agriculture Branch was aware of. Mulch remains a mainly imported product and is little promoted as an agricultural product or as significant use for a soil amendment.

Land cleared for agriculture in the Yukon tends to have a lot of trees and soils with minimal soil organic matter so it may appear counter-intuitive to burn the trees and surface organic matter off and spend up to two years growing oat or other green manure crops and ploughing them in to replace the original organic matter that was burnt off. Thus, the study sought to demonstrate if simply grinding the forest back into the soil over a matter of days provides the equivalent organic matter and soil texture the farmer pays for to remove the trees and roots, work the soil, seed, fertilize, grow, and plough back for up to two years. Isbister hypothesized the northern climate would shorten the duration of N lockup compared to warmer, wetter climates. After two growing seasons the evidence points to Isbister being correct, as the N lockup appears to have had considerably less effect on the crop by the second season. Continued cropping of the land will help us understand for just how long the effect of N lockup by wood will continue to negatively affect the crops. It is possible N stealing may be able to be offset by the addition of extra N fertilizer. Whether this is economic or not is also part of the 2024 trash blanket project.

6.4 Greenhouse Gas Emissions

The literature is not altogether unanimous regarding how much CO2 is released when burning trees, however even if one takes the view that the project’s figures are rough estimates, the Conventional treatment releases GHGs two orders of magnitude higher than the forest incorporating treatments. That one could drive a (for example) non-hybrid Honda Civic to the Moon and back, almost five times to produce the same amount of GHG that burning 1 ha of Yukon forest releases is a striking comparison. Also striking is that 1 ha of Yukon forest burning releases equivalent emissions of 306 such vehicles driving from Halifax to Vancouver, and back. Considering the subdivision of lots in which the trial took place consists of four, 65 ha lots, or 260 ha, then the clearing through burning emissions of this land conversion is the equivalent of 79,560 such vehicles making the Vancouver – Halifax return trip. Additionally, this does not include the soil organic carbon oxidized and released as GHG with the conversion of the forest soil to agriculture. In this trial, subsoiling to a depth of 12” may have been the technique releasing the most GHG from the soil carbon reserves. Release of GHG from Yukon forest soils disturbed for agriculture is the subject of future Branch research.

Although it can be considered that burning trees is carbon neutral, for agricultural land clearing the trees are not going to be allowed to regrow, so there will be no saplings on this land absorbing the released CO_2 and growing into mature trees. Even if there was, in the Yukon, to achieve carbon balance would take 100-150 years, which is arguably time that humanity does not have. Climate neutral practices are on the timescale of 20 years. This smoke and carbon release is not considered pollution nor subject to the carbon tax. If it was, the carbon tax would be worth more than the land, thus the value of carbon tax offsets would more than compensate for removing the trees by other methods, however it is not, thus burning is widely considered the cheapest option.

This project has indicated there may be techniques that are of equivalent cost, or cheapness, to burning, with possibly more beneficial effects upon the long-term health of the soil which will be investigated in future land clearing projects.

References

Aurell, J., Gullett, B., Tabor, D., & Yonker, N. (2017). Emissions from prescribed burning of timber slash piles in Oregon. *Atmospheric Environment, 150*, 395-406.

Blankinship, J. C., & Hart, S. C. (2012). Consequences of manipulated snow cover on soil gaseous emission and N retention in the growing season: a meta-analysis. *Ecosphere, 3*(1), 1-20.

Brooks, P. D., & Williams, M. W. (1999). Snowpack controls on nitrogen cycling and export in seasonally snow-covered catchments. *Hydrological Processes, 13*(14-15), 2177-2190.

Calmels, F. C., & Roy, L.-P. (2023, July 31).

Cornwall, W. (2017). *Is wood a green source of energy? Scientists are divided.* Science. doi:10.1126/science.aal0574

Environment and Climate Change Canada. (2023). *Canadian Environmental Sustainability Indicators: Greenhouse gas emissions.* Retrieved 12 7, 2023, from https://www.canada.ca/content/dam/eccc/documents/pdf/cesindicators/ghg-emissions/2023/greenhouse-gas-emissions-en.pdf

Government of Yukon. (2020). *Our Clean Future: A Yukon strategy for climate change, energy and a green economy.* Retrieved March 1, 2023, from https://yukon.ca/sites/yukon.ca/files/env/env-our-clean-future.pdf

Government of Yukon, Agriculture Branch. (2018). *InFarmation Fall 2018, Yukon Agriculture Branch Quarterly Bulletin.* Retrieved March 1, 2023, from https://yukon.ca/sites/yukon.ca/files/emr/emr-infarmation-fall-2018.pdf

Isbister, K. (2017). *Literature Review: Windrow Woodchips as a Soil Amendment for Newly Cleared Agricultural Land in Yukon.* Yukon Government, Energy, Mines and Resources; Agriculture Branch. Retrieved February 6, 2023, from https://emrlibrary.gov.yk.ca/agriculture/literature-review-windrow-woodchips-as-a-soil-amendment.pdf

Loeks, D., & Trans North Consulting. (2021). *Biolmass Fuels Industry Development Concept.* Retrieved March 1, 2023, from https://yukon.ca/sites/yukon.ca/files/biomass_fuels_industry_development_concept_0.pdf

Liniger, H. (ed) 1423211767245. (2007). *Where the land is greener: Case studies and analysis of soil and water conservation initiatives worldwide*. (Wageningen) (Netherlands) CTA/FAO/UNEP/CDE.

Mäkipää, R., Abramoff, R., Adamczyk, B., Baldy, V., Biryol, C., Bosela, M., Casals, P., Curiel Yuste, J., Dondini, M., Filipek, S., Garcia-Pausas, J., Gros, R., Gömöryová, E., Hashimoto, S., Hassegawa, M., Immonen, P., Laiho, R., Li, H., Li, Q., … Lehtonen, A. (2023). How does management affect soil C sequestration and greenhouse gas fluxes in boreal and temperate forests? – A review. *Forest Ecology and Management*, *529*, 120637. https://doi.org/10.1016/j.foreco.2022.120637

University of Maine Cooperative Extension. (2006). Bulletin #2279, Using Wood Ash on Your Farm. *Cooperative Extension Publications*. The University of Maine. Retrieved from https://extension.umaine.edu/publications/2279e/#nutrients

Appendix A: Soil Chemistry Data

DL = Analytical Method Detection Limit												
%Organic Matter, DL = 0.1												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	5.5	5.3	5.6	5.5	2.7	5.4	5.9	7.1	4.1	6.8	5.8	3.6
May-21	-	-	-	-	2.7	5.6	5.4	5.4	3.6	6.4	6.2	3.4
Oct-21	3.3	5.4	8.3	5.5	3.1	5.8	5.1	6	4.4	5.7	6.7	3.7
Jul-22	3.3	5.6	4.8	5.3	3	7.3	7	6.4	3.6	5	6.6	4.5
Sep-22	3.8	7.8	7.4	6.7	5.2	8.6	8.7	8.7	4.0	6.0	7.7	4.0
Available Nitrogen, DL = 2ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
May-21	-	-	-	-	<2	<2	<2	<2	<2	<2	<2	<2
Oct-21	2	4	2	4	<2	<2	<2	<2	<2	<2	<2	<2
Jul-22	8	7	7	7	5	8	6	9	<2	<2	<2	<2
Sep-22	<2	5	6	8	<2	<2	<2	<2	<2	<2	<2	<2
Phosphorous, DL = 5ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	10	9	13	10	43	9	18	26	23	15	10	19
May-21	-	-	-	-	21	19	25	31	31	28	28	31
Oct-21	23	24	56	26	25	19	32	29	34	25	24	26
Jul-22	26	23	16	22	19	28	26	33	22	21	18	25
Sep-22	45	60	41	39	46	34	59	60	33	28	36	36
Potassium, DL = 25ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	145	148	194	159	192	131	163	192	113	163	141	125
May-21	-	-	-	-	172	255	270	254	211	253	245	221
Oct-21	181	202	203	255	171	208	223	248	205	234	210	180
Jul-22	155	180	205	162	114	174	199	196	177	188	150	178
Sep-22	198	336	303	220	170	258	279	277	196	191	259	190
Calcium, DL = 30ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	3970	4340	4130	5110	2550	4230	3940	3460	1660	2330	2990	1240
May-21	-	-	-	-	2940	2660	3850	2520	2960	2320	4110	2210
Oct-21	1470	2890	1990	2470	1460	2480	1790	2420	2030	3450	2260	1800
Jul-22	1900	3470	3010	3090	2050	2260	2400	2200	1840	3310	2740	3270
Sep-22	1620	2740	2350	2360	1690	2030	1950	2300	1590	2850	2400	1830

Magnesium, DL = 5ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	1380	1120	1180	969	616	1160	1060	919	812	1060	1020	724
May-21	-	-	-	-	932	1090	1040	996	1010	952	1010	719
Oct-21	769	996	752	761	733	952	742	878	672	1010	917	781
Jul-22	692	1060	946	842	687	891	824	791	706	945	959	833
Sep-22	537	820	849	768	531	747	711	784	543	776	859	590
Sodium, DL = 30ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	208	249	223	216	47	235	197	147	222	168	189	72
May-21	-	-	-	-	109	221	219	153	107	184	176	118
Oct-21	111	236	113	136	71	164	157	138	63	201	150	171
Jul-22	98	304	186	173	131	193	183	141	91	218	198	192
Sep-22	48	177	146	146	99	130	90	130	39	159	136	80
Sulphate, DL = 1ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	7	93	43	350	4	55	24	18	60	6	84	3
May-21	-	-	-	-	7	59	65	23	6	88	344	39
Oct-21	26	64	17	48	4	120	21	23	6	192	21	81
Jul-22	5	76	260	18	5	43	93	13	3	201	80	100
Sep-22	3	72	35	31	6	29	13	19	2	124	13	12
Copper, DL = 0.1ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	1.9	2.4	2.3	2.1	1.1	2.4	2	2	1.1	2.6	1.9	1
May-21	-	-	-	-	1.5	2.2	2.2	2.5	1.6	1.1	1.5	0.9
Oct-21	0.7	1	0.5	1.4	0.7	0.8	0.8	0.9	0.5	0.8	0.8	0.8
Jul-22	1.2	1.8	1.5	1.4	1.1	1.3	1.4	1.3	1	1.4	1.1	1.2
Sep-22	0.8	1.2	1.1	1.1	0.8	1.1	0.8	0.9	0.7	0.8	1	0.8
Iron, DL = 2ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	38	42.3	51.8	37.4	34.5	63.9	61.8	82.5	57.2	98.8	56.6	49.5
May-21	-	-	-	-	37.6	65.5	61.6	108	37	34.9	40.4	26.1
Oct-21	20.7	33.5	34.2	27.5	21.6	44.9	34.1	38.3	19.2	25.9	35.4	40.2
Jul-22	28	48.3	42.9	38.5	29.7	55.3	50.8	68.7	26.8	29.7	34.8	42.8
Sep-22	20.3	55	54	44	27.9	56.7	47.8	56.6	19	29	33.4	46.3
Manganese, DL = 0.1ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	6.2	6.1	5.5	5	6.1	6	6	4.6	4.2	6	6.6	6.2
May-21	-	-	-	-	7.8	8.7	6.6	6.6	8.3	4.1	8.3	3.1
Oct-21	3	2.7	2	2.8	4	3.1	2.3	1.5	2.4	2.3	4.2	2.2
Jul-22	3.2	3.2	2.7	2.8	3.5	3.5	2.7	2.6	2.6	3	3.4	2.8
Sep-22	2.9	4.8	6.1	7	3.7	8.4	5.1	4.4	2.9	2.4	4.7	7.6

Zinc, DL = 0.5ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	<0.5	<0.5	<0.5	<0.5	0.9	<0.5	<0.5	0.6	<0.5	0.6	<0.5	<0.5
May-21	-	-	-	-	<0.5	<0.5	<0.5	<0.5	0.6	0.5	0.7	<0.5
Oct-21	<0.5	<0.5	0.8	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Jul-22	0.6	<0.5	<0.5	0.5	<0.5	0.9	0.6	0.7	<0.5	<0.5	0.6	<0.5
Sep-22	1	0.8	0.9	0.7	1	1	1	1	<0.5	<0.5	0.6	<0.5
Boron, DL = 0.1ppm												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	0.1	<0.1	0.1	<0.1	0.2	<0.1	0.1	0.1	0.3	0.3	0.2	0.2
May-21	-	-	-	-	0.2	0.3	0.3	0.2	0.3	0.3	0.2	0.2
Oct-21	0.3	0.3	0.5	0.4	0.3	0.3	0.3	0.3	0.4	0.7	0.3	0.3
Jul-22	0.3	0.3	0.3	0.3	0.2	0.4	0.4	0.4	0.3	0.3	0.3	0.3
Sep-22	0.6	0.7	0.7	0.5	0.5	0.7	0.8	0.7	0.4	0.5	0.6	0.5
Chloride, DL = 0.5mg/kg												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	7	9.8	6.9	6.8	4	8.4	7.1	5.7	7.2	5.6	9.2	5
May-21	-	-	-	-	7	12	12	13	7.8	14	21	10
Oct-21	6	7.8	8.6	11	4	11	7.2	6.7	7.8	10	9.4	8.8
Jul-22	10	15	11	12	9.7	14	12	12	9	18	14	14
Sep-22	7.2	12	13	11	6.8	9.4	8.8	11	6.2	14	11	10
pH												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	8.4	8.1	8.1	7.8	8.2	7.9	8.1	7.8	7.6	7.3	7.8	7.5
May-21	-	-	-	-	8.3	7.8	8	7.6	8.1	7.9	7.8	8.3
Oct-21	8.3	8.2	8	8.3	8.2	7.8	8.1	8.4	8.5	8.2	8.1	8.2
Jul-22	8.2	8.1	7.7	8	8.2	7.8	7.7	7.7	8.2	8.1	7.9	8.2
Sep-22	8	8	7.9	6.9	7.8	7.7	7.8	7.7	8.2	8.1	8	7.5
Electrical Conductivity, DL = 0.02dS/m												
	C1	C2	C3	C4	SM1	SM2	SM3	SM4	FM1	FM2	FM3	FM4
Jul-20	0.57	1	0.75	1.9	0.29	0.89	0.65	0.71	0.6	0.29	0.92	0.2
May-21	-	-	-	-	0.44	0.82	0.8	0.74	0.43	0.81	1.7	0.51
Oct-21	0.21	0.63	0.3	0.47	0.25	0.85	0.28	0.44	0.3	1.2	0.31	0.49
Jul-22	0.42	0.96	1.7	0.58	0.46	0.69	0.92	0.68	0.4	1.2	0.83	0.79
Sep-22	0.2	0.54	0.38	0.4	0.24	0.27	0.2	0.34	0.2	0.56	0.25	0.25

Appendix B: Costs and GHG calculations

(costs and calculations provided by Jonathan Lucas, YG Agriculture Branch, edited and formatted by the author)

Treatment on 4 plots, 3.7 acres per treatment
mob/demobilization charges not included
assumption: woodland burning average GHG emissions of 200t/ha
diesel GHG conversion factor = 2.681 kgGHG/L fuel*

	hours	Diesel use (l)	Diesel /hour	kg GHG from fuel	hours/acre	kg GHG/acre	wood incorporated in soil: t/acre	kg GHG released through wood burning	kg GHG released through wood burning/acre	Treatment GHG release total tonnes (& per acre)	**Cost $**
Subsoiling (FM or Forestry Mulch)											
2020											
Mulching (CMI 175[$250/hr] & 300)	17.5	604	34.51	1619.324	4.73	437.66		0			5325
Subsoiling (CMI 300 @ $350/hr)	23.5	1175	50	3150.175	6.35	851.40	74.1	0			8225
2021											
Disking	4	100	25	268.1	1.08	72.46					
Levelling	1.67	33.3	19.9	89.2773	0.45	24.13					combined
Seeding	1.5	5	3.3	13.405	0.41	3.62					
harrowing	0.83	16.7	20.1	44.7727	0.22	12.10					1560
2022											
root raking and removal	3.84	85.6	22.3	229.4936	1.04	62.03					837.44
Disking	2.33	60.67	26.0	162.65627	0.63	43.96					431.67
seeding and fertilizing	2.33	40	17.2	107.24	0.63	28.98					656.67
Treatment total	**57.5**	**2120.27**	**51.71**	**5684.44**	**15.54**	**1536.34**	**74.1**			**5.68**	**17035.78**
										1.54	4604.26

Surface Mulch (SM)											
2020											
walking down trees (D7 dozer)	4.75	66.5	14	178.2865	1.28	48.19					1575
Pushing trees into piles for chipper	10	152	15.2	407.512	2.70	110.14					1575
loading and grinding piles to mulch	24	486	48.6	1302.966	6.49	352.15					12000
2021											
Disking	4	100	25.0	268.1	1.08	72.46					
Levelling	1.67	33.3	19.9	89.2773	0.45	24.13					combined
Seeding	1.5	5	3.3	13.405	0.41	3.62					
harrowing	0.83	16.7	20.1	44.7727	0.22	12.10					1560
Loading and spreading mulch	6	175	29.2	469.175	1.62	126.80					1650
2022											
Moving wood chip piles	2.5	60	24.0	160.86	0.68	43.48					625
root raking and removing roots	20.08	427.2	21.3	1145.3232	5.43	309.55					4233.78
Disking	2.33	60.67	26.0	162.65627	0.63	43.96					431.67
seeding and fertilizing	2.33	40	17.2	107.24	0.63	28.98					656.67
Loading, spreading, re-piling woodchips	21.5	305	14.2	817.705	5.81	221.00					3552.5
Clean up leftovers from chipping/root raking	4	81.5	20.4	218.5015	1.08	59.05					870
Treatment total	**105.49**	**2008.87**	**298.40**	**5385.7805**	**28.51**	**1455.62**	**74.1**			**5.39**	**28729.62**
										1.46	7764.76
Conventional Slash and Burn (C)											
2020											
walking down trees (D7 dozer)	4.75	66.5	14	178.2865	1.28	48.19					1575
Piling for burning	5.33	72	13.51	193.032	1.44	52.17					1575
Burning & Re-piling & Burning 2022	22.5	135	6.00	361.935	6.08	97.82					2225
Burning Trees 2022								485829.96	131305.3945		
2021											
Disking	4	100	25.0	268.1	1.08	72.46					

Levelling	1.67	33.3	19.9	89.2773	0.45	24.13					combined
Seeding	1.5	5	3.3	13.405	0.41	3.62					
harrowing	0.83	16.7	20.1	44.7727	0.22	12.10					1560
2022											
root raking and removing roots	20.08	427.2	21.3	1145.3232	5.43	309.55					4233.78
Disking	2.33	60.67	26.0	162.65627	0.63	43.96					431.67
seeding and fertilizing	2.33	40	17.2	107.24	0.63	28.98					656.67
Clean up leftovers from chipping/root raking	4	81.5	20.4	218.5015	1.08	59.05					870
Treatment total	**69.32**	**1037.87**	**186.76**	**2782.5295**	**18.74**	**752.03**		**485829.96**	**131305.39**	**488.61**	**13127.12**
										132.06	3547.87

* from National Inventory Report 1990-2021: Greenhouse Gas Sources and Sinks in Canada, Part 2, Table A6.1-5, "Emission Factors for Refined Petroleum Products" accessed through https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/emission-factors-reference-values.html#toc4