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Spatial Structure and Process of Arctic Warming and Land Cover Change in the Feedback Systems Framework

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Abstract**—**This paper examines the relationships between and among the various drivers of climate change that have both climatic and ecological consequences for vegetation and land cover change in arctic areas, particularly in arctic Alaska. It discusses the various processes that have created spatial and climatic structures that have facilitated observable vegetation and land cover changes in the Arctic. Also, it indicates that the drivers of both climatic and ecological changes in the Arctic are multi-faceted and operate in a system with both positive and negative feedbacks that largely results in further increases or decreases of the initial drivers of climatic and vegetation change mainly at the local and regional scales. It demonstrates that the impact of arctic warming on land cover change and the Arctic ecosystems is not unidirectional and one dimensional in nature but it represents a multi-directional and multi-dimensional forces operating in a feedback system.

Keywords**—**Arctic Vegetation Change, Climate Change, Feedback System, Spatial Process and Structure.

I. Introduction

ARCTIC land cover, particularly arctic Alaska land cover has undergone considerable change over the years. This change is symptomatic of increasing vegetation specie change (increasing shrub growth), change in snow accumulation, change in albedo, decrease in ice and permafrost cover, decrease in snow depth and increase in snowmelt, changes in soil moisture, changes in water quality (turbidity and sedimentation), and changes in water nutrient and the onset of these factors [1]-[6]. The present study defines the Arctic as areas largely covered by ice, snow, and permafrost [7]. This area represents one of the ecosystems in the world with limited human influence [7]. As a result of global warming, induced land cover changes in this part of the world provide key indications of the extent of the overall impact of climate change on the world's ecosystems and the global terrestrial environment as a whole. Land cover change in this study represents changes in the composition and distribution of land surface features such as vegetation, ice, snow, and permafrost covers over a given period due to anthropogenic or natural temperature variability forcings or both over that giving period. Global warming (climate change) under pins the recent trend in arctic land cover and vegetation changes through increases in arctic temperature and summer warmth [5]-[12]. The Arctic has experienced considerable warming in recent decades with an average mean temperature of about 3 ^{0}C with a corresponding mean temperature range between 3-5 ^{0}C over the land mass [13]. In all, over the past 30 years the Arctic warmed on the average of 2 ^{0}C per decade [14]. Greenhouse gases emissions and sun solar irradiance are the main drivers of the recent and past decades arctic warming, particularly the early part of the 20th century to present [8]-[11], [15]-[28]. The current warming trend of the Arctic is expected to increase depicting a mean temperature between 4-5 ^{0}C by the year 2080 [13]. Temperature increases due to increases in atmospheric greenhouse gases emission is expected to increase global mean temperature by 1.0-3.5 ^{0}C over the next century [29]. These temperature increases have both ecological and environmental consequences in that temperature impacts almost all chemical and biological processes [29].

The current global temperature increase and that of arctic Alaska is mainly attributed to increases in the emission of greenhouse gases into the atmosphere. A number of studies have argued that recent temperature increases, especially in the 1990s other than the warming period between 1920s-1930s (natural causes) are attributed to anthropogenic forcing characterize by increasing emission of greenhouse gases into the atmosphere [5], [8], [11]. The principal greenhouse gases that are contributing substantially to the current increasing temperature trend are carbon dioxide (CO_2), nitrous oxides (N_2O), chlorofluorocarbons (CFC), and methane (CH_4) [1], [8]-[12], [30], [31], [32], [33], [22]. The authors of references [1], [33] and [34], [40] indicated that though global increases in greenhouse gases contributes substantially to global warming trend world-wide and increases in regional and local temperatures in the Arctic the resultant increase temperature in the Arctic could create further increases in temperature of arctic areas including arctic Alaska. Their observations are based on the increasing thawing and the declining extent of arctic ice cover that form a significant part of the arctic carbon storage base commonly referred to as the arctic carbon sink. Recent increasing release of arctic carbon dioxide into the atmosphere contributes to the disruption of the global carbon dioxide budget associated with positive atmospheric heating feedback[3],[29],[34]-[36].

Additionally, the literature reveals the possible impact of the North Atlantic Oscillation (NOA) on arctic climate change [1], [37], [38]. The author of reference [37] noted that arctic oscillation (AO) influence less than half of the warming in arctic Alaska. Furthermore, they indicated that long term changes in NAO affect local differences in arctic temperature

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and snow accumulation that has implications for changes in vegetation composition and distribution [38], [39]. On the other hand, the authors of reference [1] intimated that NAO effects on winter warming is more pronounce in Eurasia than in arctic Alaska. Instead, Pacific North America Teleconnection (PNAT), Pacific Decadal Oscillation (PDO), and El Nino-Southern Oscillation have a stronger influence on arctic Alaska winter temperatures with relatively weak impact on summer temperatures.

The relationship between global warming and arctic vegetation change are two folds: direct and indirect. The authors of reference [5] noted that the extent of this relationship has not yet been fully quantified. This study proposes to examine the direct and indirect effect of global warming on arctic vegetation change based on the feedback systems framework and the processes of arctic warming and land cover change.

II. The Relationship between Global Warming and Arctic Vegetarion Change

Direct impact of temperature change on arctic vegetation reflects the changing vegetation specie composition and distribution in respect of increases in warmth loving plant species over the cold loving species. Available research on the relationship of the response of arctic vegetation to climate change suggests that arctic vegetation is sensitive to climate change [1], [5], [22]. An assessment of annually dated fossil pollen record suggests that arctic plant species range and abundance vary with respect to temperature differences [22]. Also, the authors of reference [1] reported from their assessment of paleoclimate data of arctic areas that arctic summers are getting warmer and this has consequences for changes in vegetation constituent (species) and the distribution of vegetation in arctic regions.

In examining the rate of increase of summer temperatures of Alaska and Western Canada the authors of reference [1] indicated that summer temperatures increased from the range of 0.15 – 0.17^{o}C per decade (1961-1990 and 1966-1995) to 0.3 – 0.4 ^{o}C per decade (1961-2004). Furthermore, their analysis, which is supported by indigenous and derived satellite image vegetation indices revealed that increase in summer temperature by 1-2 ^{o}C for the past 20-30 years, resulted in the increase of shrub vegetation growth in Alaska. In addition, the authors of reference [2] noted that total summer warmth (TSW) and elevation are strongly correlated with normalized vegetation index (NDVI) of Alaska. However, TSW was stronger in explaining changes in NDVI than elevation. In their study 'the circumpolar vegetation map' the authors of reference [2] reemphasized the sensitivity of arctic vegetation to climate change. Here they underscored the fact that changes in summer temperature can result in changes in vegetation structure, species diversity, plant productivity, and altitudinal and zonal vegetation boundaries. Their findings largely coincide with the observation that increases in temperature over the past decades in arctic areas have largely contributed to the observable changing vegetation composition and distribution [1], [2], [4], [5].

As temperatures increase in Arctic areas in respect of the global trend in increasing temperature (global warming), ecosystems respond and adjust to the prevalent climate conditions. One of these adjustments, particularly in the Arctic and specifically in Alaska is the change in vegetation composition from the typical tussock tundra vegetation type to the shrub and tree like vegetation [1], [2], [4], [5], [6]. Evidence in available literature on the impact of climate change (increase in temperature) on vegetation change suggests that a positive relationship exist between them [1], [2], [4], [5], [6]. This type of change is expected since the increase in temperature and the corresponding changes in the onset of summer largely provide the necessary environment for warmth loving plants (shrubs) to thrive and increase in growth as compared to the tussock tundra less warm loving vegetation species [1], [3], [6].

The authors of reference [15] attributed shrub expansion in Northern Alaska and the Arctic to climate warming. They found that Northern Alaska shrub has expanded over the past 50 years with a 620 km east to west extent and 350 Km north to south extent. Also, they noted that shrub in Alaska have grown in size. The authors of reference [1] intimated that increase in shrub growth and tree-like vegetation in arctic areas has the potential for creating further increases in arctic summer warmth thereby compounding the effect of temperature increases on vegetation change in favor of shrub vegetation in arctic Alaska and other arctic regions.

Additionally, increase in shrub and tree like vegetation could lead to increase above ground carbon storage [36]. The change in the composition of arctic vegetation in response to the global increasing trend in temperature has both global and local ecological consequences. Locally, this effect may manifest in the loss of local and indigenous plant species [3], [6] as well as limit the availability of animal food. The authors of reference [6] document the declining availability of forb specie that is important for Caribous during lactation.

Arctic albedo change that measures the reflective and absorptive capacity of arctic land cover surfaces mainly characterizes the direct effect of global increases in temperature on ecosystem and vegetation changes. Surface albedo serves as a key factor in modeling climatic change forces and for explaining ecological processes [44]. As temperature increases and ice covered areas in the Arctic decrease substantially, the net short wave energy reflected into the atmosphere largely decreases [1]. Conversely, long wave heat energy transferred into the atmosphere largely increases per the decreased ice cover areas increase [1]. This creates further atmospheric warming with time signifying a direct impact of increasing temperature on arctic land cover change. The decreasing albedo associated with decreases in the extent of ice cover areas through increasing temperatures largely lead to increase vegetation growth in favor of woody plants in arctic areas. As woody plant growth increase in the arctic areas, tree canopy per a giving area (plan community and functional groups) largely increase. The area covered by leaf canopy of these woody plants and their shadows reduces the reflecting surfaces of ice cover areas in which they are situated. This phenomenon largely creates an in balance in the reflection capacity of ice cover areas due to sun insulation over the absorptive capacity of tree cover areas. This result in the increase in net energy reradiated in to the atmosphere, thus creating further increase in temperature at that local or regional scale and ultimately affecting the global increasing temperature trend ([1], [31], [32]. In their study on the 'Role of land-surface changes in arctic summer warming' authors of reference [1] indicated that increasing snow melt advance in arctic Alaska of about 2.5 days per decade resulted in the absorption and transfer of 26 MJ m^{-2} into the atmosphere within the same period. Their analysis suggests the importance of albedo change that leads to ice melt and increasing transfer of energy into the atmosphere that largely compounds the existing increasing temperature trend. According to authors of references [1] and [11] the effects of changing albedo that reflect increasing in net transfer of energy in to the atmosphere due to land cover and vegetation changes are comparable to the effect of carbon dioxide emission into the atmosphere.

Coupled with albedo changes in arctic areas are the general increases in ice/snowmelt and permafrost thaw and shrub expansion form part of the indirect effects of temperature increases on arctic land cover change. Ice/glaciers in Alaska is melting at a relatively fast rate (30 percent) due to temperature increases in the latter part of last century (1950-1990) [7]. The authors of reference [7] intimated that giving the 20^{th} century rate of ice melt, the Grand Union glacier in western Alaska is predicted to completely disappear by 2035. In examining the impact of ice melt in the arctic region they noted that the recent National Aeronautic and Space Administration (NASA) surveyed glacier extent of Greenland revealed a decrease in glacier extent with a corresponding ice melt runoff comparable to one of the large Siberian rivers. Though this observation is limited to Greenland, the impact of such a massive runoff and the associated volume of water could have global ecological and environmental implications. In addition to snowmelt, increasing melting trend associated with early onset of snow free season and decreasing winter snow accumulation are observable in arctic Alaska. Early onset of snow free period, early plant growth season, and increase release of carbon dioxide (CO_2) and methane (CH_4) are some of the ecological implications of snowmelt [7]. With respect to permafrost thaw both continuous and discontinuous permafrost thawing are observable in Alaska. The effects of temperature change on discontinuous permafrost warm rates indicate an increase from 0.05-0.2 to 0.5-1.5 ^{o}C [7]. Besides temperature other factors that influence permafrost thaw and warming are vegetation cover, thermal properties of the surface cover and substrate, soil moisture, and mode of heat transfer [7]. Permafrost thaw and warming causes dramatic changes of affected ecosystem and the creation of thermokars, slumping, and small puddle or ponds [7]. As early spring temperature increases and vegetation specie composition and distribution change, more sun insulation is absorbed, which is converted from insensible short wave energy to sensible long wave heat energy that warms the earth surface [31], [32]. In arctic Alaska where large proportion of the surface is covered by ice related materials (snow, permafrost) an increase in surface temperature results in further melting of ice/snow and thawing of permafrost surface materials. Evidence from available literature largely confirms the general increasing in ice/snowmelt and permafrost thawing that has consequences for land cover, vegetation, ecological changes [1], [8],[10]. These studies note that early onset of arctic summer period and the late conclusion of the same resulting in relatively warmer winters contributes substantially to the rate of ice/snowmelts and permafrost thawing [8],[10]. The authors of reference [8] intimated that winter period for the coming century is likely to be 40 percent warmer than its global equivalent. This observation is consistent with effect of summer and autumn/fall warming that account for about 40 percent of thinning of arctic sea ice in recent years [10]. In concert with these observations, the authors of reference [1] reported that arctic snowmelt dates has increase over the past decade from 1.5 to 3.5 days per decade in arctic Alaska with spring soil thaw (permafrost thaw) dates increase from 2.2 to 3.3 days per decade for North American and Eurasia tundra areas. This change corresponds to increases in leaf out dates of 2.7 and 4.3 days per decade for arctic Alaska and North America and Eurasia tundra areas respectively thereby depicting the response of arctic vegetation to temperature increases and its associated increases in ice/snowmelt and permafrost thawing rates as discussed by the authors of reference [1]. The authors of reference [42] estimated that snow-shrub interaction could lead to 10 to 25 percent wide spread increase in winter snow depth in relation to the increase, abundance, size, and coverage of arctic shrub in response to increasing temperature.

Nor does ice/snowmelt and permafrost thaw influence terrestrial vegetation change but also lake turbidity and sedimentation rate that affect primary production and life forms in affected lakes. The authors of reference [23] indicate that arctic lakes limnology will continue to be influenced by climate change and the warming of the Arctic. In relation to this assertion, the authors of reference [7] noted that one of the consequences of arctic glacial loss is increase deposition of dissolve organic matter and sediments into water bodies. As ice/glacier, snow, and permafrost thaw surface runoff increase the volume of water bodies and turbidity through the deposition of land surface materials including sediments and terrestrial organic matter into these water bodies largely increase. This phenomenon largely limits the availability of sunlight for photosynthesis and primary productivity, which defines the production of basic food materials for lake life forms, especially the bentic community [7]. The authors of reference [23] cited for example that sediment from arctic shallow ponds and lakes Ellesmere and Devon Islands that resulted from the mid-19^{th} century warming led to acute changes in lake diatom algae flora. Also, the deposition of terrestrial sediments composed of dissolve organic carbon largely supports the production of large quantities of bentic invertebrate [46]. Furthermore, increasing inflow of surface water into lakes has implications for lake water chemistry. The increasing summer (1975-2000) alkalinity level of Lake

Toolik typifies this situation [7]. However, full explanation for the increasing summer alkalinity level of Lake Toolik has not yet been provided though the authors of reference [7] suggest that weathering of new unfrozen glacial till, atmospheric deposition through rain alkalinity, amount of surface flow through the active layer may explain this phenomenon. Among these factors they explained that rain alkalinity does not offer sufficient explanation for the occurrence of this phenomenon because both rainfall amount and chemical composition has not changed very much between 1975 and 2000. Based on this observation and the review of available literature the present study postulates that vegetation type, geologic surface type (old versus new), elevation, and slope that largely determines the type and composition of surface materials and the rate of flow of these materials into Toolik Lake may offer more additional plausible explanation to the recent increases in Toolik Lake alkalinity.

In addition to the temperature related factors, soil pH (acidity or alkalinity of soil) and geologic surface type (old and new till) limit the distribution of vegetation types at both functional group and plant species levels in arctic Alaska [6], [31],[32], [33]. The literature largely portray that the impact of these factors on vegetation change and plant species distribution form one of the factors that limit vegetation distribution and change in arctic Alaska [2], [5], [44], [45]. The impact of soil pH and substrate type stems from different levels of plant affinities for soil acidity or alkalinity and old till or new till surfaces. The effect of soil pH is well documented in the literature. Distribution and categorization of arctic Alaska vegetation into moist acidic tundra (MAT) and moist non-acidic tundra (MNT) typifies the effect of soil pH on vegetation distribution and change. Traditionally, moist acidic tundra thrive on acidic soil with a top mineral horizon pH value <5.5 and dwarf shrub as the dominant life form. Conversely, moist non-acidic tundra thrive on alkalinic soil with a mineral top pH value >6.5 with tussock graminoid as the dominant plant form [2], [5], [44], [45]. In all, arctic vegetation is limited largely by soil pH, which affects plant nutrients and help create distinct plant communities [1], [5], [44]. Notwithstanding the effect of land cover change on regional and local weather the effects of arctic warming on arctic vegetation change has attracted relatively less global attention. The authors of reference [7] indicated that arctic ecosystem characterized by land cover changes contributes (positive feedback) to changes in local climatic condition and hydrology. They argued that the arctic present a several but related factors that account for global, regional, and local ecological variability. They emphasized that no one single factor could sufficiently explain the relationship between climate and ecosystem changes and that the respective factors that account for these changes in the Arctic operate as a system.

In line with this observation the present study examined the spatial interrelationships between climate and vegetation changes based on the premise that spatial factors that create spatial structure of vegetation change and the processes by which these changes are created are circularly causal and interrelated [1], [50], [51]. This is because spatial process of increasing arctic warming due to global warming leads to changes in spatial structure characterized by land cover changes in arctic Alaska that mainly result from global increases in temperature (global warming), albedo changes and increasing ice/snowmelt and permafrost thaw. As these spatial structure changes occur more energy is released into the atmosphere through albedo changes that intensify atmospheric warming that creates further increases in temperature. Also, spatial changes in ice/snowmelt and permafrost thawing produce more liquid water in arctic areas, which results in increases in atmospheric water vapor through the process of evaporation and transpiration. The increasing release of terrestrial carbon dioxide into the atmosphere and its corresponding impact on global warming exemplifies the impact of land cover change (spatial structure) on the process of global warming. These relationships create positive atmospheric heating feedback, which form one of the parameters that the feedback systems approach, a subtype of process-response systems approach hinges on. The spatial process-response systems approach examines the effects of related elements on each other within a system [50]. According to the author of reference [50] process-response systems approach provide studied processes of causal interrelationships. He described the feedback systems as the nuclei of the systems theory of change. Specifically, the feedback systems characterize by positive feedback (morphogenetic) and negative feedback (morphostatic/homeostatic) together with spatial structure-process theory form the main tool (conceptualization) for examining the relationship between temperature increases and arctic land cover changes [46], [47].

III. Discussion: Spatial Process and Structure in the Feedback System Framework of Arctic Warming and Land Cover Change

As indicated above arctic warming has both direct and indirect impact on land cover change through increases in land surface temperature [1], [3], [6], [7], [13], [22], [23], [11], [35], [36], [39], [42], [48]. These impacts work through various pathways to produce positive atmospheric heating feedback [46]. Though negative atmospheric cooling feedback is possible in situations where decrease albedo and snow/ice melt create bare surface largely devoid of vegetation, the present study did not consider the direct impact of negative atmospheric cooling feedback because bare surfaces in arctic Alaska are relatively small. As a result, it is unlikely for such impact to cause a significant negative atmospheric cooling and land cover change that can significantly impact the recent trend of temperature increase through recent warming trend of the Arctic.

The authors of reference [7] intimated that arctic ecosystem is characterized by complex and interrelated systems that require complete and holistic examination in other to account for and elucidates the contributions of arctic ecosystems forces with particular reference to the recent global and arctic warming trends. They underscored the fact that these forces are interrelated and cannot be studied in isolation in an attempt to gain complete understanding of the extent to which these processes influence arctic warming and land cover change. Their assertion indicates that arctic spatial structure of land cover change, particularly ecosystem change and the underlying processes that create them are circularly causal as espoused by authors of reference [47].

The state of the arctic climate and local weather conditions at a given period is conceptualized as the atmospheric structure of that area (Fig. 1).

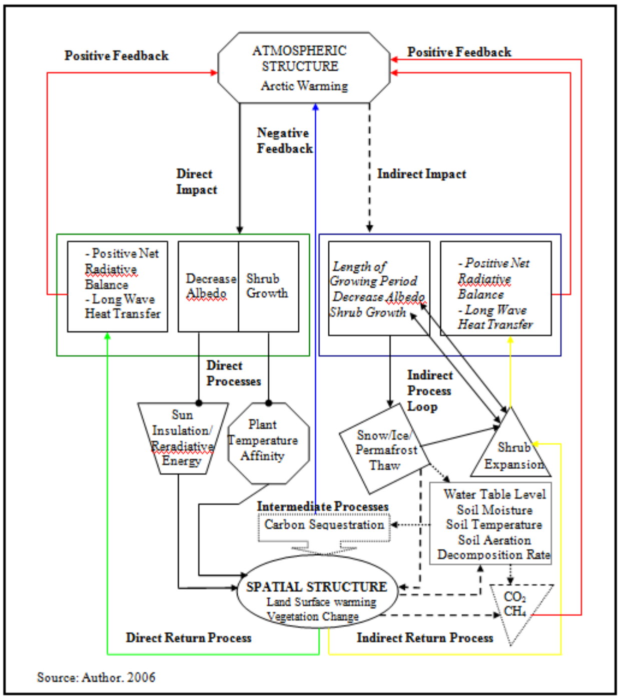

Fig. 1 **S**patial process-structure interrelationships and the feedback systems framework of arctic warming and land cover change

On the other hand, the nature of the surface of the study area representing land cover is denoted as surface structure in this framework (Fig. 1). The various mechanisms through which arctic atmosphere is warmed and land cover is change depicts spatial processes of both atmospheric and land cover changes. These processes exert both direct and indirect impact on atmospheric and land cover changes. Base on spatial structure-process theory arctic warming atmospheric structure influence arctic surface structure by causing corresponding land cover change through direct processes of length of warming period, net heat radiative balance, and plant temperature affinity, and indirect processes of shrub expansion and snow/ice/permafrost thaw underlying this change. Change in surface structure exemplified by land cover change in turn creates further warming of the atmosphere through reverse direct and indirect processes of positive radiative balance and long wave heat energy transfer into the atmosphere. Given that conditions that create this relationship remain constant, the warming of the atmosphere could lead to further changes in arctic surface structure that primarily determine the extent of land cover change encapsulating the interrelationship between arctic warming and land cover change as circularly causal.

The feedback systems approach as explained the author of reference [46] typifies the relationship between arctic warming and land cover change. This is premised on the fact that the arctic is epitomized by a complete system with elements that are interrelated [7]. Coupling with the theory of spatial structure-process is the feedback systems approach that explains the interrelationships between the elements that create spatial structure and the processes through which spatial structure is created. Spatial structure in turn amplifies the extent of spatial process, which creates further changes in spatial structural and the respective feedbacks associated with these interrelationships. This feedback systems approach is composed of two parts; the direct and indirect impacts primarily characterized by positive or morphogenetic atmospheric heating and negative or morphostatic/ homeostatic atmospheric cooling feedback systems (Fig. 1). The present study views these interrelationships as operation in a bi-dimensional feedback systems environment.

IV. Conclusion

In respect of the circularly causative nature of the relationship between arctic warming and surface land cover changes, especially increase shrub growth in arctic Alaska this study supports the findings of other related studies indicated above that these relationships have consequences for local and regional ecosystems stability. The pathways and various interrelated linkages in the conceptual framework (Fig. 1) demonstrate that the impact of arctic warming on land cover change and ecosystems is not unidirectional and one dimensional in nature but it represents a multi-directional and multi-dimensional forces operating in a feedback system underpin by spatial structure and process interrelationships.

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3. Urban Growth and Peri-urban Land Use Change in Accra, Ghana: A Remote Sensing and GIS Analysis (2003). Geography M.A. Thesis. Binghamton University, New York, USA. United States Copyright 2010.
4. The role of Remote Sensing in Space Activities and its relevance to the society. Space Generation Advisory Council (SGAC) Newsletter, December 2009. With Ms. Ariane Cornell, Executive Director, SGAC and Mr. Michael Kio, SGAC Regional Coordinator for Africa.