

Review

REPRODUCTIVE BIOLOGY OF THE GROUND-DWELLING SQUIRRELS

Syed Uzair Ahmad

Department of Biological Sciences, Karakoram International University, Gilgit, Pakistan

Received May 2008, accepted November 2008

Summary: Most species of ground-dwelling squirrels are hibernating seasonal breeders that reproduce under environmental and climatic constraints. Hibernators pass 5-8 months in underground hibernacula each year by subsisting on body fats stored during previous summer. Activation of the hypothalamic-hypophyseal-gonadal axis takes place following terminal arousal from torpor, gonadal recrudescence occurs post-hibernation, sometimes including a pre-emergence period when the animal is still sequestered in the hibernaculum, and mating takes place shortly after emergence from hibernation. Litters are born underground and first emerge above ground when about 4-5 week old. Among rodents, ground-dwelling squirrels are reported to have the highest reproductive energy demands from mothers. The gonadal steroid feedback to gonadotropin release is absent in females and in males it is inoperative during breeding season but functions during reproductive quiescence. Increased testosterone levels coincide with vernal reproductive activities, but progesterone levels in both parous and non-parous females remain elevated in summer and decline in autumn and winter. Variable degrees of reproductive suppression, which may also involve stress-mediated reproductive inhibition along with other mechanisms, are reported for some ground-dwelling species. Circannual cycles of these animals simulate natural photoperiods, but unlike other seasonal breeders, ground squirrels cannot be entrained to constant changes in photoperiod, rather run free for less than 365 days. This paper discusses the salient features of reproductive biology of the ground-dwelling squirrels in relation to hibernation, stress and photoperiodism.

Keywords: ground-dwelling squirrels, reproduction, breeding, hormones, stress, circannual rhythm, hibernation

Introduction

Family Sciuridae of the order Rodentia includes ground-dwelling squirrels of subfamily Sciurinae represented by *Spermophilus* (ground squirrels; GSs), *Marmota* (marmots), *Tamias* (chipmunks) and *Cynomys* (prairie dogs) genera. Most species of ground-dwelling squirrels are obligate hibernators and seasonal breeders that live in diverse habitats and they exhibit remarkable physiological adaptations to seasonal environmental factors. Ground-dwelling squirrels exhibit a variety of social systems and mating sys-

tems, and some engage in cooperative breeding [1-2]. Research on sciurids has focused on behavioral ecology [3-5], behavioral endocrinology [6-12], circannual cycles [13-15] and hibernation [16-18]. One species of marmots (woodchuck; *M. monax*) is used in biomedical research as a model for several human conditions, such as hepatitis, primary hepatocellular carcinoma, obesity and vascular diseases [19-21]. Ground-dwelling squirrels can be potential subjects for physiological research on the pubertal processes of non-seasonal breeders because, as seasonal breeders, they experience gonadal recrudescence

Address for correspondence:

Dr. Syed Uzair Ahmad, 4, Ali Street, Phulgran Road, Shahpur, Barakahu, Islamabad
Phone: 051 2230388 / 0323 5335478, E-mail: syed.uzair.ahmad@gmail.com

Short running title: Ground Squirrel: Reproduction

on an annual basis. However, scientific information regarding the reproductive biology of the ground-dwelling squirrels is fragmentary, though some aspects such as mating behavior are well-studied. Therefore, this paper attempts to synthesize the available information on various aspects of reproductive biology of sciurids and explores related factors that may directly or indirectly affect their reproduction.

Hibernation in ground-dwelling squirrels

With a few exceptions most species of ground-dwelling squirrels are obligate hibernators that spend autumn, winter, and part of spring each year in underground hibernacula. Some species aestivate in summer. Incidence of hibernation differs among closely related species; for example, the white-tailed prairie dog (*Canis leucurus*) is a deep obligate hibernator, whereas the black-tailed prairie dog (*C. ludovicianus*) is a facultative hibernator at high altitudes and latitudes, with other populations never exhibiting hibernation [22-25]. In arctic GSs adult females enter in hibernacula during July, adult males and juvenile females during August and September and juvenile males during October. Within a species, different age and sex classes usually start and terminate hibernation at different times; for example, adult males emerge from hibernation before adult females in almost all species and juveniles enter hibernation later than adults [26,27]. Chipmunks, which start hibernation later than GSs and marmots, also rely on cached food, whereas all other ground-dwelling squirrels generally rely on body fat stores [28]. Late entry into hibernation may not necessarily be related to food intake always as juvenile Richardson's GSs (*S. richardsonii*) do not hibernate until October but still depend on fat rather than seeds [3]. In captivity, lack of food and low temperature are the major inducers of hibernation and, if imposed late during their normal hibernation period, do not trigger hibernation in captive animals [29] indicating that hibernation is an adaptive re-

sponse to low temperatures and food shortage in free living conditions. However, in the wild, in some species such as Richardson's GSs and Anatolian GSs (*S. xanthoprymnus*); certain cohorts start hibernation in June and July when food is plentiful and temperatures are still increasing [3] indicating the role of some other inducing factors.

During 5 to 8 months (mo) of hetero-thermy season, ground-dwelling squirrels conserve energy by lowering body temperatures to near ambient soil temperatures; in some situations falling as low as -2°C [30,31]. Before entering hibernation, brown adipose tissue and metabolic machinery increase 2-3 fold [32,33]. During hibernation, bouts of torpor (deep hypothermia; 80-90% of hibernation period) are periodically interrupted by intervals of spontaneous arousals (normal body temperature) of a few hours (hrs) [34]. Many physiological and cellular processes including respiration, digestion, renal metabolism, mitosis, translation and immune function are arrested during hibernation [35,36]. Even in the non-hibernating state, ground-dwelling squirrels tolerate hypoxia and ischemia better than non-hibernating animals [37]. Heart rate decreases to 1% of the euthermic state during torpor, yet the heart recovers without fibrillation to beat normally during each inter-bout arousal [38,39] with remarkable property of neuroprotection from ischemia and hypoxia even when cerebral blood flow decreases 80-90% during torpor [18,37,40]. However, after hibernation ground-dwelling squirrels exhibit reduced performance in hippocampal-dependent memory tasks including a diminished ability to recognize previously familiar squirrels, though they retain the ability to recognize littermates and other close kin [41-43]. Such remarkable properties of hibernators even in the absence of environmental cues may be attributed to their molecular genetics [44] which make them physiologically distinguished from non-hibernators to cope with an environment with high carbon dioxide and low

oxygen levels.

Increased secretion of testosterone (T) at the end of heterothermy is associated with earlier emergence of adult males from hibernation than subadult males or adult females. Furthermore, much higher incidence of hibernation in captivity by females than by males indicates that T may have a hibernation-related role in ground-dwelling squirrels [45]. In several other hibernating mammals, such as hamsters, implantation of T-filled silastic capsules inhibits torpor [46]. In castrated golden-mantled GSs (*S. lateralis*), the administration of high T concentration (comparable to those of intact males at the end of hibernation season) prevents entry into hibernation while moderate concentrations of T reduce torpor duration [47]. Furthermore, castration 1-3 week (wk) after terminal arousal from torpor can reinstate hibernation in this species [48]. It has been opined that a T-independent mechanism may trigger arousal from torpor but T-dependent processes are involved in reinstating torpor at the end of an arousal period [47]. Thyroid hormone and prolactin (PRL) also begin to rise around the time of terminal arousal from torpor [11] and may affect the transition from hibernation to active life and subsequent reproductive activities.

Hibernation is a well-regulated process and many parts of brain appear to be involved in controlling seasonal heterothermy. The suprachiasmatic nucleus (SCN) of the hypothalamus which is a circadian pacemaker also affects hibernation but in a different manner. In the golden-mantled GSs, metabolic activities in the brain decrease markedly as animals enter torpor, whereas metabolic activities increase in the SCN and ablation of the SCN increases duration of torpor bouts and hibernation incidence [17]. Within the brain, turnover of norepinephrine, dopamine, serotonin, thyrotropin-releasing factor and endorphin decreases during hibernation but vasopressin, enkephalin and histamine levels increase. Histaminergic neurons found in many parts of brain

are involved in the regulation of hibernation such as hippocampus and brainstem reticular formation [49]. Melatonin circadian rhythm is thought to be involved in timing hibernation in the ground-dwelling squirrels [50]. Such observations suggest that the regulation of hibernation involves complex neural pathways intricately linking many aspects of animal physiology under an endogenous oscillator that time seasonal activities under environmental constraints.

Body mass cycle

Ground-dwelling squirrels exhibit annual variable seasonal body mass cycle (marmots weigh several kg whereas small *Spermophilus* species such as 13-lined GS weigh less than 250 g). In hibernating species of ground-dwelling squirrels, body weight increases 25-100% over the active season and then declines by 25-50% during hibernation [19,51]. There is less disparity in emergence weights between males and females, but males gain weight more rapidly and achieve higher peaks than do females irrespective of sex differences in gonadal hormone secretion [52,53]. Majority of studies have utilized captive sciurids to understand the mechanisms of body mass cycle. *Ad libitum* fed golden-mantled GSs also exhibit a circannual rhythm in body mass due almost entirely to fluctuations in fat reservoirs in captivity [54]. However, in gonadectomized golden-mantled GSs, estrogen (E) treatment during both mass gain and mass loss phases reduces the amplitude of annual cycle [15]. In captive woodchucks, food intake and respiratory quotient correlate with free thyroxin (T_4) levels [55] and T_4 levels are highest in spring, which then decline in summer, are at nadir in early autumn, and increase slightly in early winter. Coincidentally, PRL levels also increase in late winter and early spring which is associated with increase in relative food intake [11]. On the other hand, high leptin concentrations are associated with decrease in food intake [12], and leptin administration disrupts circannual rhythm

of feeding behavior and body weight gain in arctic GSs [44,56,57]. Since animals face much more complicated situation in the wild than in captivity, it can be assumed that circannual cycle of body mass is regulated by an endogenous oscillator by interacting with many sensory and physiological processes. Yet the neuroendocrine mechanisms of such an oscillator are not yet fully understood.

Mating

In the ground-dwelling squirrels, mating systems are usually either monogamous or polygynous but polyandry does exist. Generally, more social species such as hoary marmots (*M. caligata*), Vancouver Island marmots (*M. vancouverensis*) and Olympic marmots (*M. olympus*) are monogamous with only a few populations exhibiting polygyny while in others such as woodchucks and yellow-bellied marmots (*M. flaviventris*) relatively lower sociality is associated with polygyny [58]. Group size may also influence mating pattern as in hoary marmots smaller groups usually consist of a monogamous pair, whereas polygyny is prominent in larger groups [59]. It is thought that monogamy is more likely to occur in resource-limited habitats and where the reproducing pair may suppress reproduction of the other members of the group, presumably for the sake of warming juveniles during hibernation [60].

In smaller species, both sexes of ground-dwelling squirrels achieve sexual maturity as yearlings. However, in larger species of *Spermophilus* and in *Cynomys* and *Marmota*, males often do not breed until 3 or 4 years of age and females may not breed until at least 2 years of age (Michener, pers com). Among marmots, Vancouver Island marmot, Olympic marmot, and hoary marmot attain sexual maturity at three years of age [61-63] while sexual maturity is achieved earlier by yellow-bellied marmots [64] and later by golden marmots (*M. caudata*) [4]. Like many

other mammals, ground-dwelling squirrels exhibit variable degree of cooperative breeding. In alpine marmots (*M. marmota*), males help in warming and thus increasing offspring survival during hibernation. In these animals, mothers can produce more sons when helpers are needed but have unbiased sex ratio of the offspring when helpers are present [65]. On the other hand, black-tailed prairie dogs, which are the most socially integrated among the ground-dwelling squirrels, exhibit the least cooperative breeding [66].

Adult males emerge from hibernation a couple of wk earlier than females in most species [45] which provides time for testicular recrudescence and spermiogenesis to be completed by the time females emerge from hibernation and this maximizes their mating opportunities in a polygynous system [28,34]. Gonadal recrudescence in both sexes takes place after terminal arousal from torpor; in some species, males remain sequestered in the hibernaculum after terminal arousal, so recrudescence occurs in the post-hibernation pre-emergence period and is energetically expensive because males are still exposed to cold soil temperatures [34]. In some species such as Richardson's GSs, after emerging from hibernation, males exhibit a dynamic territoriality depending on the availability of estrous females which are receptive for a short period after emerging from hibernation [67,68]. Most ground-dwelling squirrels are monoestrous [69,70] and induced ovulators [71] with the estrus period varying from a few hrs to 27 days depending on mating opportunities [70,72,73]. However, in free living conditions, estrus period usually remains very short. Ovulation occurs within 10-36 hrs post-copulation and mated females terminate estrus within 12-72 hrs [6,71]. The long estrus period and induced ovulation may serve to ensure optimum reproductive success by increasing mating chances [6]. Mating seasons in spring last for 1-4 wk depending on the species and year [14,34,71], and gestation period in various ground-dwelling squirrel species ranges be-

tween 23 and 40 days. Females give birth to a single litter during March to June, depending on the species and geographic location [6,7,29, 65,74-76], and pups are weaned after 4-6 wk. In adults of both sexes, gonadal regression occurs during summer [14,34,51].

The annual cycle of heterothermy has profound effects on endocrine and reproductive systems, and females tend to optimize litter size to their physical condition and social circumstances [77]. Thus, time management affects reproductive output of sciurids as early emerging females mate earlier and have larger litters with more male offspring. Late-reproducing females tend to wean their offspring at a younger age in an effort to prepare for hibernation [78]. Higher reproductive investment of females than that of males may lead to low overwinter survival or a delayed estrus in the next season [6,29]. Maternal reproductive investment during lactation among rodents is reported to be quite high for sciurids [75], especially for yearlings [79]. In alpine marmots and golden marmots, the amount of food resources is directly related to the number of offspring weaned [80]. In wild populations of arctic GS (*S. parryii*), addition of food is reported to increase the percentage of females that lactate, increase litter size and population density [81-84].

Hypothalamic-hypophyseal-gonadal axis

In ground-dwelling squirrels, elevation in luteinizing hormone (LH) is associated with the onset of the breeding season [34]. In captive golden-mantled GSs, peak LH concentrations are higher and earlier in males than in females with LH levels peaking during spring and summer and then declining to low or undetectable levels during autumn and winter. In females, hypothalamic-hypophyseal-gonadal (HPG) axis runs independent of gonadal steroid feedback. Thus, castration during early life leads to an early rise in LH

secretion, but an equivalent phenomenon does not occur in gonadectomized females. This sex difference can be reversed by neonatal androgenization of females [53,85]. In males, testicular negative feedback to LH is inoperative during breeding season but works during rest of the year. Plasma LH levels persistently elevate within a few days after bilateral orchidectomy, whether performed before or after breeding season in adults. Gonadectomy of prepubertal (2.5 mo old) male GSs leads to a relatively brief peak in plasma LH which is followed by restoration of near baseline levels for 3 mo whereas there is a more sustained elevation of LH in older animals after gonadectomy [86]. Thus, sex steroid imprinting in ground-dwelling squirrels appears to involve some unique aspects especially in development of gonadal feedback to gonadotropins. In woodchucks, administration of pregnant mare serum gonadotropin and human chorionic gonadotropin in combination for four wk markedly stimulates testicular growth (increase in volume, diameter and luminal area of seminiferous tubules) and restores spermatogenesis in the regressed testes. Such a hormonal stimulation also results in a significant rise in serum T levels and testicular T content (without changing Leydig cell number), which is also associated with a marked increase in epithelial height in accessory reproductive glands [87]. Similarly, estrus can be induced in sexually quiescent woodchucks by exogenous administration of gonadotropins [70]. Activation of gonadotropin secretion in hibernating juvenile ground-dwelling squirrels is delayed up to 1 mo than in juveniles that could not hibernate when housed under identical conditions [46]. These observations show that ground-dwelling squirrels have evolved annual rhythm of HPG axis under selection pressures of cold and food shortage that works under an endogenous oscillator to time seasonal reproductive activities in a harsh environment where spells for active life are just enough for juvenile growth before their first hibernation.

Testicular cycle

Testes are fully regressed before ground-dwelling squirrels enter hibernation, and in many species gonadal maturation is almost complete by the time they emerge from hibernation but a few species exhibit poorly developed gonads on emergence [34]. In laboratory conditions, testicular recrudescence is observed in the absence of hibernation, with testis enlargement and T secretion independent of food and light deprivation [45]. At the start of heterothermy in golden-mantled GSs, seminiferous tubules are small, without a lumen and the germinal epithelium consists of only spermatogonia and Sertoli cells. Reproductive maturation in this group during heterothermy consists of slight increase in gonadal mass but there is no spermatogenesis beyond the pachytene stage [34,46]. Usually, within a few days after the terminal arousal from torpor, gonadotropin and androgen levels increase leading to rapid testis growth with the completion of meiosis and spermiogenesis. In this pre-emergence period, plasma T levels are moderate but sufficient to maintain spermatogenesis. After emergence from hibernation, T levels increase to concentrations that may be necessary for reproductive behavior and mating. Nearly 10 wk post-hibernation, gonadotropins and androgen return to near basal levels, spermatogenesis ceases, and testes are regressed [46,51]. However, in captive woodchucks, there is a transient hypertrophy and hyperplasia of interstitial cells after the breeding season [45]. Whereas in many species such as California GSs (*S. beecheyi*) and golden-mantled GSs, T levels remain high only during the mating season, T levels in arctic GSs are high both at the mating period and at the end of the summer [27]. It is postulated that high T levels mediate aggressive behavior for intra-sexual mating competition and are associated with defending territories in late summer. In arctic GSs, the adrenal gland rather than the testis appears to produce higher quantities of T under corticotropin stimulation and non scrotal males

exhibit high T levels [27].

Persistent T levels only elevate near the end of heterothermic season and not during inter-bout arousals when T levels increase marginally, indicating that testicular maturation in ground-dwelling squirrels starts at the end of hibernation and peaks during post-torpor pre-emergence period under an endogenous oscillator. Such a mechanism may involve increased T responsiveness or a decrease in sensitivity of feedback inhibition of LH by T during the last part of heterothermy [46]. In golden-mantled GSs, gonadotropin stimulation of androgen secretion does not occur at torpid temperatures *in vitro* [88]. There is some circumstantial evidence that reduction in torpor frequency (longer inter-bout arousal) during the hibernation season advances testicular development [34]. Furthermore, exposition to warmer temperatures (30°C) during late hibernation leads to earlier sexual maturation [89]. On the other hand, in captive golden-mantled GSs, precocious cooling (20 wk exposure at 6°C in the fall) results in earlier onset of pigmented scrotum and descended testes compared with the controls. The precocious cold exposure also appears to affect circannual rhythm as in some animals enlarged descended testes persist for more than a year [90].

Threshold levels of body fats appear to be permissive for testicular growth. Juvenile male golden-mantled GSs previously held at 23°C and fed a high-fat diet then underwent hibernation, weighed more and exhibited higher plasma T levels than the chow-fed controls following hibernation [91]. High concentrations of leptin have an inhibitory and low leptin levels have stimulatory effect on gonadotropin secretion. A possible role of leptin in the seasonal reproductive activities in the ground-dwelling squirrels is evident from studies of woodchucks in which serum concentrations of leptin are very low when gonadal recrudescence starts and increases during gonadal regression [12]. Captive ground

squirrels tolerate low temperatures better than marmots during hibernation [4,16], and male yearling woodchucks are not a significant component of the breeding population unlike golden-mantled GSs, in which T levels are similar in captive yearlings and adults [92]. However, species differences in body mass may also contribute to this feature. Histaminergic activities in the brain increase during hibernation, may be at some point histamine modulates the circannual oscillator's trigger of gonadal recrudescence, as in reptiles, histamine can increase or decrease T production at low or high concentration, respectively [93]. Taken together, ground-dwelling squirrels display some unique physiological traits of testicular recrudescence which permit them to prepare for vernal activities before the commencement of breeding season in extremely harsh environment and processing of temperature-related sensory information appears to be much complicated in these animals.

Ovarian cycle

In ground-dwelling squirrels, elevated serum E levels during pre-estrus and estrus are associated with increase in vaginal cornification and leukocyte infiltration [6]. Once animals become anestrus, E levels drop after a week post-estrus [70]. Besides inducing behavioral estrus, E also maintains copulatory neuroendocrine reflexes. Unmated females exhibit a prolonged estrus. In many ground-dwelling squirrels, the presence of males and mating stimuli considerably influence estrus, presumably because of induced ovulation. In *Spermophilus* species, females without access to males have significantly higher E levels during estrus and metestrus phases than those with access to males [6]; however, normally all females in free-living populations do have access to males and usually all mate shortly after they enter estrus. In woodchucks, ovulation of 6-10 ova is followed by a marked increase in serum progesterone (P) levels [71]. In pregnant woodchucks, the number of

uterine implantations is never more than the number of corpora lutea (CL) and transcornual embryo migration is prevented by a duplex cervix. The CL are larger afterwards than during pregnancy and persist 3-4 mo postpartum along with elevated serum P levels independent of suckling. Less than 25% subadult (<2 years old) females become pregnant and, as yearlings (1 year old), they have several small CL [74,94]. Non-parous females which luteinize spontaneously, like parous females, have elevated P levels in late spring and early summer [14]. Progesterone levels are higher and rise approximately 2 wk earlier in non-parous adult woodchucks than in non-parous yearlings, whereas P levels in adult and yearling California GSs (which are sexually mature) rise simultaneously but yearlings exhibit lower P levels compared to adults throughout the breeding cycle. Whereas high P tends to inhibit lactogenesis in other rodents, it appears unlikely in ground-dwelling squirrels since P levels are highest during lactation and healthy offspring are weaned [95].

Though P profile of alpine marmots and yellow-bellied marmots is similar to that of woodchucks, in alpine marmots there is a transient decrease in P levels soon after parturition, followed by recovery after several hours [7]. In the prairie dogs which are monoestrous spontaneous ovulators [96], the CL remains active and P levels are high for 14 wk in the breeding season. In unmated black-tailed prairie dogs, which are monoestrous spontaneous ovulators, P concentration increase spontaneously within 2 weeks of estrus which are maintained for 8-10 wk. However, P levels are relatively lower than those of pregnant and postpartum females [96]. In the thirteen-lined GSs (*S. tridecemlineatus*) which maintain secretory CL for at least 2 months postpartum, the placenta is unable to provide P required to maintain pregnancy as ovariectomy of pregnant females results in fetal resorption or abortion [95]. In alpine marmots, peripheral relaxin concentrations increase significantly dur-

ing the early part of pregnancy indicating its primacy in implantation rather than in parturition in this species [7]. In primates relaxin secretion is also high during first trimester of pregnancy and low in the third trimester, whereas in pigs and rats its levels are associated with parturition [97]. Thus, the selection pressures for optimizing female reproduction in the ground-dwelling squirrels have led to the evolution of many characteristics with species-specific repertoires such as monoestrus reproductive cycles, persistent high P levels after parturition and even capabilities to adjust sex ratios of offspring, making these animals distinct from other groups of mammals.

Reproductive suppression and stress

Ground-dwelling squirrels exhibit variable degree of reproductive suppression. However, in most *Spermophilus* species, reproductive suppression is almost absent in females as all females wean litters. In alpine and golden marmots, one female reproduces per social group, whereas in yellow-bellied marmots (*M. flaviventris*) reproductive suppression is low [98]. In such ground-dwelling species, subordinates are debarred from reproductive opportunities by dominant individuals. Dominant males, which are usually territorial, attack unrelated subordinate males, and in some large species dominant females frequently behave agonistically with subordinate females [99]. In sciurids, infanticide is exhibited by both the sexes but in some species it is a predominant male behavior [100] which is more common in black-tailed prairie dogs and golden marmots [101]. Males taking over a territory or social group may kill the progeny of the loser [102]. In the majority of ground-dwelling squirrels, there is a significant skewing of sex ratios among adults in favor of females which in breeding animals further intensifies as a significant number of breeding males die immediately after the breeding [103] owing to stressful intense competition for access to females.

Ground-dwelling squirrels face a variety of stressors that may affect their reproduction. Chronic stress may be due to unpredictable decreased food supply, social status, population density, habitat quality and predation [8,104]. In a nine-year study of wild arctic GSs, removal of predators significantly improved litter size and percentage of females that lactated and weaned litters [81] besides increasing population density [105]. Sources of acute stress include attempted infanticide, agonism during mating competition, low food availability, and exposure to unfamiliar locations and conspecifics during natal or breeding dispersal [8]. Adrenal glands of Belding's GSs (*S. beldingi*) are largest about 1 month after emergence from hibernation then decrease sharply afterwards [8]. Captive European GSs (*S. citellus*) show low glucocorticoid (GC) levels after hibernation, followed by an increase during and after reproduction [106]. On the other hand, chipmunks have low GC levels during the mating period, highest levels during lactation, and GC levels are again low in summer when juveniles emerge and enter the above-ground population [107]. Alarm calling in response to predators in marmots is associated with higher concentrations of fecal GC metabolites [9].

Stress is known to activate the hypothalamic-pituitary-adrenal (HPA) axis leading to increased body metabolism. Thus an exhaustive metabolism as a result of intense chronic stress may cause infertility, inhibition of growth, and impaired resistance to diseases. In male arctic GSs, which undergo stressful intrasexual competition, reproduction increases mortality, with 50% of adult males dying soon after breeding. In this species, adult breeding males exhibit the highest levels of free cortisol, the lowest maximum cortisol binding capacity and a very poor immune response compared with populations with low stress. Stressed animals also have low hematocrit and fewer white blood cells, but more

eosinophils than animals with less stress [108,109]. The conventional dogma for stress-mediated reproductive suppression focuses on HPA-HPG nexus emphasizing that reproductive inhibition precedes release of corticotropin releasing hormone and β -endorphin which suppress gonadotropin releasing hormone (GnRH) secretion. Peripherally, GCs suppress androgen production by affecting action of gonadotropins on sex steroid-producing cells and by decreasing pituitary responsiveness to GnRH. Such mechanisms may participate in pubertal delay, suppression of ovulation, blocks to implantation and spontaneous abortion [10].

However, the role of HPA axis in stress-mediated reproductive suppression remains obscure. An increase in T levels in arctic GSs following ACTH injection suggests that natural stressors such as aggression may augment T levels rather than suppressing it. Juvenile male arctic GSs in mid-August face chronic stress associated with dispersal but still their T levels are elevated [27]. In male yellow-pine chipmunks, T levels decline and GC levels tend to peak after the mating period. Though exogenous T significantly reduces plasma GC levels in post-reproductive male chipmunks, the ability to increase GC levels in response to trap-related stressor remains intact, even when T levels are high [110]. Therefore, besides well established mechanisms of suppressing reproductive metabolism by increased HPA activity, species differences do exist to challenge this generalization. Furthermore, it is well established that during early postnatal life, whereas high GC levels adversely affect behavioral learning, moderately elevated GC levels significantly improves associative and spatial learning in rodents including sciurids; juvenile squirrels learn appropriate anti-predation behaviors soon after emergence from natal burrow, a time when they have to face stress from predators and infanticidal conspecifics [104].

Circannual rhythms

In the ground-dwelling squirrels, annual changes in body mass, hibernation, and reproduction are governed by temperature-compensated circannual rhythms which are not actually derived from, but rather synchronized or entrained by, the photoperiodic cycle [111]. Thus, under natural photoperiodic conditions, a circannual rhythm last for 12 mo but under constant or manipulated photoperiods it may last for less than 12 mo i.e. run free [13]. Such rhythms are difficult to precisely describe because it is often not feasible to isolate animals (which usually have short life spans) from all environmental variables that influence cycle [15]. Entrainable circannual rhythms are also reported for serum PRL, T_4 , and leptin in captive woodchucks [11,12]. Whereas block (constant) changes in photoperiod such as persistent long/short days and transition from long days to short days cannot perturb the circannual cycle, photoperiods involving daily changes that simulate natural photoperiods prevent free running [11]. In woodchucks, transition from Northern Hemisphere (boreal) to the Southern Hemisphere (austral) photoperiods leads to approximately 6 mo phase advanced entrainment in the body weight and gonadal cycles after 28 mo [14]. In contrast, circannual cycles in several species of non-sciurid rodents such as hamsters, voles, sheep, deer, ferrets, and mink are highly dependent on the photoperiod zeitgeber. In these rodents circannual cycles are readily desynchronized by neutral photoperiod, or phase-shifted or re-entrained by block changes in photoperiod [51, 112].

In the ground-dwelling squirrels, seasonal circadian variations in locomotor activity too are regulated by a circannual clock which is neither dependent on nor influenced by concurrent changes in secretion of gonadal hormones [113]. In golden-mantled GSs kept in constant light at

22°C for several years, the circadian locomotor rhythm does not correspond exactly to photoperiod, but is less than 24 hrs in summer and greater than 24 hrs during winter and the seasonal patterns recur at 10.5 mo interval [114]. Seasonal changes in the duration of nocturnal melatonin secretion appear to be necessary to produce such phase delays required to entrain the circannual clock to a period of 12 mo [115]. In marmots, during extremely short photoperiods (8L:16D and 4L:20D), plasma melatonin levels remain high longer. The pineal gland may also influence body temperature regulation through the daily melatonin secretory profile [50] and alterations in circannual rhythms have been reported in golden-mantled GSs upon lowering temperatures in the fall and spring [90]. Whereas, melatonin treatment in late summer phase shifts reproductive and body mass rhythms of juvenile female GSs durably; it is ineffective if carried out in spring [114].

Conclusion

Reproduction is a costly exercise for hibernating species of ground-dwelling squirrels whose annual cycle of activity and hibernation is characterized by reproduction shortly after the end of the lengthy heterothermal period. As is typical of most mammals, males incur the stress of intra-sexual competition and females incur the stress of gestation and lactation. Hibernation has a profertility effect and hibernators must prepare for the upcoming heterothermic period after they have completed reproductive activities for the season. Whereas gonadotropins are pro-reproductive hormones, prolactin, leptin, and gonadal steroids also have roles in hibernation-reproduction nexus in sciurids. Different species of ground-dwelling squirrels exhibit variable degrees of reproductive suppression and stress-mediated mortality. Ground-dwelling squirrels exhibit annual variable seasonal body mass, reproductive and endocrine cycles constituting circannual rhythms that are not derived, rather en-

trained by natural photoperiod unlike most of other seasonal breeders. The fragmentary knowledge of the reproductive biology of the ground-dwelling squirrels provokes quests in many areas such as the mechanisms underlying gonadal recrudescence, hibernation-reproduction nexus, role of adrenal and HPA axis in reproduction, and mechanisms of circannual rhythms. Some unique aspects of HPG axis such as sex steroid feedback to gonadotropin secretion in ground-dwelling squirrels make them useful models for studying neuroendocrine mechanism involved in neural plasticity leading to GnRH neuron maturation / activation. Unique endocrinological observations such as persisting elevated postpartum P levels and the notion that adrenals may produce T under pituitary stimulation in arctic GSs invites further investigations. Ground-dwelling squirrels can also be a good model to study the mechanisms by which GCs inhibit responsiveness of pituitary cells to GnRH which appears to be influenced by sex steroids. In Pakistan Himalayas, Karakoram and Hindukush ranges provide habitat to two species of marmots (Himalayan marmot and golden marmot) which can be useful models for behavioral and physiological studies.

Acknowledgments

The author is grateful to the referees for their critical evaluation and assistance in improving this review.

References

1. **Armitage, K.B.** 1981. Sociality as a life-history tactic for ground squirrels. *Oecologia*. 48:36–49.
2. **Arnold, W.** 1990. The evolution of marmot sociality II: Costs and benefits of social hibernation. *Behav. Ecol. Sociobiol.* 27:239–246.
3. **Michener, G.R.** 1984. Age, sex and species differences in the annual cycles of ground-dwelling sciurids: implications for sociality. In: *Biology of ground-dwelling squirrels: annual cycles, behavioral ecology and sociality*. Eds. Murie, J.O. and Michener, G.R., University of Nebraska Press.

4. **Blumstein, D.T. and Arnold, W.** 1998. Ecology and social behavior of golden marmots. *J. Mammal.* 79:873–886.
5. **Blumstein, D.T.** 2007. The evolution, function, and meaning of marmot alarm communication. *Adv. Study Behav.* 37:371–401.
6. **Millesi, E., Huber, S., Pieta, K., Walz, M., Arnold, W. and Dittami, J.P.** 2000. Estrus and estrogen changes in mated and unmated free-living European ground squirrels. *Horm. Behav.* 37:190–197.
7. **Exner, C., Wehrend, A., Hospes, R., Einspanier, A., Hoffmann, B. and Heldmaier, G.** 2003. Hormonal and behavioural changes during the mating season and pregnancy in alpine marmots (*Marmota marmota*). *Reprod.* 126:775–782.
8. **Mateo, J.M. and Cavigelli, S.A.** 2006. A validation of extraction methods for noninvasive sampling of glucocorticoids in free-living ground squirrels. *Physiol. Biochem. Zool.* 78:1069–1084.
9. **Blumstein, D.T., Patton, M.L. and Saltzman, W.** 2006. Faecal glucocorticoid metabolites and alarm calling in free-living yellow-bellied marmots. *Biol. Lett.* 2:29–32.
10. **Jackson, T.P., Waterman, J.M. and Bennett, N.C.** 2007. Pituitary luteinizing hormone responses to single doses of exogenous GnRH in female social Cape ground squirrels exhibiting low reproductive skew. *J. Zool.* 273:8–13.
11. **Concannon, P.W., Castracane, V.D., Rawson R.E. and Tennant, B.C.** 1999. Circannual changes in free thyroxine, prolactin, testes, and relative food intake in woodchucks, *Marmota monax*. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 277:1401–1409.
12. **Concannon, P., Levac, K., Rawson, R., Tennant, B. and Bensadoun, A.** 2001. Seasonal changes in serum leptin, food intake, and body weight in photoentrained woodchucks. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 281:951–959.
13. **Zucker, I., Boshes, M. and Dark, J.** 1983. Suprachiasmatic nuclei influence circannual and circadian rhythms of ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 13:472–480.
14. **Concannon, P.W., Roberts, P., Baldwin, B. and Tennant, B.** 1997. Long-term entrainment of circannual reproductive and metabolic cycles by northern and Southern Hemisphere photoperiods in woodchucks (*Marmota monax*). *Biol. Reprod.* 57:1008–1015.
15. **Heibert, S.M., Lee, T.M., Licht, P. and Zucker, I.** 1998. Estradiol phase shifts circannual body mass rhythms of male ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 274:754–759.
16. **Arnold, W., Heldmaier, S., Pohl, O.H., Ruf, T. and Steinlencher, S.** 1991. Ambient temperature in hibernacula and their energetic consequences for alpine marmots (*Marmota marmota*). *J. Thermal Biol.* 16:223–226.
17. **Ruby, N.F., Dark, J., Burns, D.E., Heller, H.C. and Zucker, I.** 2002. The suprachiasmatic nucleus is essential for circadian body temperature rhythms in hibernating ground squirrels. *J. Neurosci.* 22:357–364.
18. **Ma, Y.L., Zhu, X., Rivera, P.M., Toien, O., Barnes, B.M., LaManna, J.C., Smith, M.A. and Drew, K.L.** 2005. Absence of cellular stress in brain after hypoxia induced by arousal from hibernation in Arctic ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 289:1297–1306.
19. **[My papYoung, R. and Sims, E.]** 1979. The woodchuck, *Marmota monax*, as a laboratory animal. *Lab. Anim. Sci.* 29:770–780.
20. **Tennant, B.C. and Gerin, G.L.** 2001. The woodchuck model of hepatitis B virus infection. *ILAR J.* 42:89–102.
21. **McKenzie, E., Jackson, M., Sun, J., Volotovskyy, V. and Gruwel, M.L.H.** 2005. Monitoring the development of hepatocellular carcinoma in woodchucks using 31P-MRS. *Magnetic Resonance Materials in Physics, Biol. Med.* 18:201–205.
22. **Harlow, H.J. and Frank, C.L.** 2001. The role of dietary fatty acids in the evolution of spontaneous and facultative hibernation patterns in prairie dogs. *J. Comp. Physiol. Biochem. Syst. Environ. Physiol.* 171:77–84.
23. **Lehmer, E.M., Savage, L.T., Antolin, M.F. and Biggin, D.E.** 2005. Extreme plasticity in thermoregulatory behaviors of free-ranging black-tailed prairie dogs. *Physiol. Biochem. Zool.* 79:454–467.
24. **Lehmer, E.M., vanHorne, B., Kulbartz, B. and Flotrant, G.L.** 2001. Facultative torpor in free-ranging black-tailed prairie dogs (*Cynomys ludovicianus*). *J. Mammol.* 17:103–128.
25. **Lehmer, E.M., Bossenbrock, J.M. and vanHorne, B.** 2003. The influence of environment, sex and innate timing mechanisms on body temperature patterns of free-ranging prairie dogs (*C. ludovicianus*). *Physiol. Biotech. Zool.* 76:72.83.
26. **McLean, I.G. and Towns, A.J.** 1981. Differences in weight changes and the annual cycle of male and female arctic ground squirrels. *Arctic* 34:249–254.
27. **Boonstra, R., McColl, C. J. and Karels, T.J.** 2001. Reproduction at all costs the adaptive stress response of male arctic ground squirrels. *Ecol.* 82:1930–1946.
28. **Place, N.J., Veloso, C. and Kenagy, G.J.** 2002. Energy expenditure and testosterone in free-living male yellow-pine chipmunks. *J. Exp. Zool.* 292:460–467.

29. **Concannon, P.W., Fullam, A., Baldwin, B.H. and Tennant, B.C.** 1989. Effects of induction versus prevention of hibernation on reproduction in captive male and female woodchucks (*Marmota monax*). *Biol. Reprod.* 41:255–261.
30. **Barnes, B.M.** 1989. Freeze avoidance in a mammal: body temperatures below 0°C in an Arctic hibernator. *Sci.* 244:1593–1595.
31. **Michener, G.R.** 1992. Sexual differences in torpor patterns in Richardson's ground squirrels in natural hibernacula. *Oecologia* 89:397–406.
32. **Barger, J.L., Barnes, B.M. and Boyer, B.B.** 2006. Regulation of UCP1 and UCP3 in arctic ground squirrels and relation with mitochondrial proton leak. *J. Appl. Physiol.* 101:339–347.
33. **Yan, J., Burman, A., Nichols, C., Alila, L., Showe, L.C., Showe, M.K., Boyer, B.B., Barnes, B.M. and Marr, T.G.** 2006. Detection of differential gene expression in brown adipose tissue of hibernating arctic ground squirrels with mouse microarrays. *Physiol. Genomics* 25:346–353.
34. **Barnes, B., Kretzmann, M., Licht, P. and Zucker, I.** 1986. The influence of hibernation on testis growth and spermatogenesis in the golden-mantled ground squirrel, *Spermophilus*. *Biol. Reprod.* 35:1289–1297.
35. **DiBona, G.F.** 2003. Thermoregulation. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 284:277–279.
36. **Kauffman, A.S., Paul, M.P. and Zucker, I.** 2004. Increased heat loss affects hibernation in golden-mantled ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 287:167–173.
37. **Dave, K.R., Prado, R., Raval, A.P., Drew, K.L. and Perez-Pinzon, M.A.** 2006. The arctic ground squirrel brain is resistant to injury from cardiac arrest during euthermia. *Stroke* 37:1261–1269.
38. **Belke, D.D., Wang, L.C.H. and Lopaschuk, G.D.** 1997. Effects of hypothermia on energy metabolism in rat and Richardson's ground squirrel hearts. *J. Appl. Physiol.* 82:1210–1218.
39. **van Breukelen, F. and Martin, S.L.** 2002. Molecular biology of thermoregulation. Invited Review: Molecular adaptations in mammalian hibernators, unique adaptations or generalized responses. *J. Appl. Physiol.* 92:2640–2647.
40. **Zhou, F., Zhu, X., Castellani, R.J., Stimmelmayer, R., Perry, G., Smith, M.A. and Drew, K.L.** 2001. Hibernation, a model of neuroprotection. *Am. J. Pathol.* 158:2145–2151.
41. **Mateo, J.M. and Johnston, R.E.** 2000. Kin recognition and 'armpit' effect; evidence for self-referent phenotype matching. *Proc. Royal Soc. Lond.* 267:695–700.
42. **Millesi, E., Prossinger, H., Dittami, J.P. and Fieder, M.** 2001. Hibernation effects on memory in European ground squirrels (*Spermophilus citellus*). *J. Biol. Rhythms* 16:264–271.
43. **Von Der Ohe, C.G., Garner, C.C., Darian-Smith, C. and Heller, H.C.** 2007. Synaptic protein dynamics in hibernation. *J. Neurosci.* 27:84–92.
44. **Carey, H.V., Andrews, M.T. and Martin, S.L.** 2003. Mammalian hibernation cellular and molecular responses to depressed metabolism and low temperature. *Physiol. Rev.* 83:1153–1181.
45. **Baldwin, B.H., Tennant, B.C., Reimers, T.J., Cowan, G. and Concannon, P.W.** 1985. Circannual changes in serum testosterone concentrations of adult and yearling woodchucks (*Marmota monax*). *Biol. Reprod.* 32:804–812.
46. **Barnes, B., Kretzmann, M., Zucker, I. and Licht, P.** 1988. Plasma androgen and gonadotropin levels during hibernation and testicular maturation in golden-mantled ground squirrels. *Biol. Reprod.* 38:616–622.
47. **Lee, T.M., Pelz, K., Licht, P. and Zucker, I.** 1990. Testosterone influences hibernation in golden-mantled ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 259:760–767.
48. **Dark, J., Miller, D.R. and Zucker, I.** 1996. Gonadectomy in the spring reinstates hibernation in male golden-mantled ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 270:1240–1243.
49. **Sallmen, T., Beckman, A.L., Stanton, T.L., Eriksson, K.S., Tarhanen, J., Tuomisto, L. and Panula, P.** 1999. Major changes in the brain histamine system of the ground squirrel, *Citellus lateralis*, during hibernation. *J. Neurosci.* 19:1824–1835.
50. **Florant, G.L. and Tamarkin, L.** 1984. Plasma melatonin rhythms in euthermic marmots (*Marmota flaviventris*). *Biol. Reprod.* 30:332–337.
51. **Concannon, P.W., Roberts, P., Baldwin, B., Erb, H. and Tennant, B.** 1993. Alteration of growth, advancement of puberty, and season-appropriate circannual breeding during 28 months of photoperiod reversal in woodchucks (*Marmota monax*). *Biol. Reprod.* 48:1057–1070.
52. **Zucker, I. and Boshes, M.** 1982. Circannual body weight rhythms of ground squirrels: role of gonadal hormones. *Am. J. Physiol.* 243:546–551.
53. **Smale, L., Pelz, K., Zucker, I. and Licht, P.** 1986. Neonatal androgenization in ground squirrels: influence on sex differences in body mass and luteinizing hormone levels effects of FGF9 on embryonic Sertoli cell proliferation and testicular cord formation in the mouse. *Int. J. Dev. Biol.* 48:637–643.
54. **Dark, J., Stern, J.S. and Zucker, I.** 1989. Adipose tissue dynamics during cyclic weight loss and weight

- gain of ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 256:1286–1292.
55. **Rawson, E., Concannon, P.W., Roberts, P.J. and Tennant, B.C.** 1998. Seasonal differences in resting oxygen consumption, respiratory quotient, and free thyroxine in woodchucks. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 274:963–969.
 56. **Ormseth, O.A., Nicolson, M., Pelleymounter, M.A. and Boyer, B.B.** 1996. Leptin inhibits prehibernation hyperphagia and reduces body weight in arctic ground squirrels. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 271:1775–1779.
 57. **Boyer, B.B., Ormseth, O.A., Buck, L., Nicolson, M., Pelleymounter, M.A. and Barnes, B. M.** 1997. Leptin prevents posthibernation weight gain but does not reduce energy expenditure in Arctic ground squirrels. *Comp. Biochem. Physiol. Pharmacol.* 118:405–412.
 58. **Armitage, K.B. and Johns, D.W.** 1982. Kinship, reproductive strategies, and social dynamics of yellow-bellied marmots. *Behav. Ecol.* 11:55–63.
 59. **Kyle, C.J., Karels, T.J., Davis, C.S., Mebs, S., Clark, B., Strobeck, C. and Hik, D.S.** 2006. Social structure and facultative mating systems of hoary marmots (*Marmota caligata*). *Mol. Ecol.* doi: 10.1111/j.1365-294X.2006.03211.x
 60. **Allaine, D.** 2000. Sociality, mating system and reproductive skew in marmots: evidence and hypotheses. *Behav. Processes* 51:21–34.
 61. **Kruckenhauser, L., Pinsker, W., Haring, E. and Arnold, W.** 1999. Marmot phylogeny revisited: molecular evidence for a diphyletic origin of sociality. *J. Zool. Syst. Evol. Res.* 37:49–56.
 62. **Steppan, S.J., Akhverdyan, M.R., Lyapunova, E.A., Fraser, D.G., Vorontsov, N.N., Hoffmann, R.S. and Braun, M.J.** 1999. Molecular phylogeny of the marmots (Rodentia: Sciuridae): tests of evolutionary and biogeographic hypotheses. *Syst. Biol.* 48:715–734.
 63. **Bryant, A.A.** 2005. Reproductive rates of wild and captive Vancouver Island marmots (*Marmota vancouverensis*). *Can. J. Zool.* 83:664–673.
 64. **Schwartz, O.A., Armitage, K.B. and Van Vuren, D.** 1998. 32-year demography of yellow-bellied marmots (*Marmota flaviventris*). *J. Zool. Lond.* 246:337–346.
 65. **Allaine, D.** 2004. Sex ratio variation in the cooperatively breeding alpine marmot, *Marmota marmota*. *Behav. Ecol.* 15:997–1002.
 66. **Michener, G.R. and Murie, J.O.** 1983. Black-tailed prairie dog coteries: Are they cooperatively breeding units. *Am. Naturalist* 121:266–274.
 67. **Michener, G.R. and McLean, I.G.** 1996. Reproductive behaviour and operational sex ratio in Richardson's ground squirrels. *Anim. Behav.* 52:743–758.
 68. **Michener, G.R.** 1998. Sexual differences in reproductive effort in Richardson's ground squirrels. *J. Mammal* 79:1–19.
 69. **Michener, G.R.** 1980. Estrous and gestation periods in Richardson's ground squirrels. *Mammol.* 61:531–534.
 70. **Hikim, A.P.S., Woolf, A., Bartke, A. and Amador, A.G.** 1991b. The estrous cycle of captive woodchucks (*Marmota monax*). *Biol. Reprod.* 44:733–738.
 71. **Hikim, A.P.S., Woolf, A., Bartke, A. and Amador, A.G.** 1992. Further observations on estrus and ovulation in woodchucks (*Marmota monax*) in captivity. *Biol. Reprod.* 46:10–16.
 72. **Holmes, W.G. and Landau, I.T.** 1986. Vaginal estrus in unmated Belding's ground squirrels. *Horm. Behav.* 20:243–248.
 73. **Landau, I.T. and Holmes, W.G.** 1988. Mating of captive thirteen-lined ground squirrels and the annual timing of estrus. *Horm. Behav.* 22:474–478.
 74. **Concannon, P., Baldwin, B. and Tennant, B.** 1984. Serum progesterone profiles and corpora lutea of pregnant, postpartum, barren and isolated females in a laboratory colony of woodchucks (*Marmota monax*). *Biol. Reprod.* 30:945–951.
 75. **Michener, G.R.** 1989. Reproductive effort during gestation and lactation by Richardson's ground squirrels. *Oecologia* 78:77–86.
 76. **Dobson, F.S. and Michener G.R.** 1995. Maternal traits and reproduction in Richardson's ground squirrels. *Ecol.* 76:851–862.
 77. **Risch, T.S., Michener, G.R. and Dobson, F.S.** 2007. Variation in litter size a test of hypotheses in Richardson's ground squirrels. *Ecol.* 88:306–314.
 78. **Millesi, E., Huber, S., Everts, L.G. and Dittami, J.P.** 1999. Reproductive decisions in female European ground squirrels: factors affecting reproductive output and maternal investment. *Ethol.* 105:163–175.
 79. **Broussard, D.R., Michener, G.R., Risch, T.S. and Dobson, F.S.** 2005. Somatic senescence: evidence from female Richardson's ground squirrels. *Oikos* 108:591–601.
 80. **Blumstein, D.T. and Foggin, J.M.** 1997. Effects of vegetative variation on weaning success, over winter survival and social group size in golden marmot. *J. Zool. Lond.* 243:57–69.
 81. **Karels, T.J., Byrom, A.E., Boonstra, R. and Krebs, J.K.** 2000. The interactive effects of food and predators on reproduction and overwinter survival of arctic ground squirrels. *J. Anim. Ecol.* 69:235–247.

82. **Dobson, F.S.** 1995. Regulation of population size: evidence from Columbian ground squirrels. *Oecologia* 102:44–51.
83. **Dobson, F.S. and Kjelgaard, J.D.** 1985a. The influence of food resources on population dynamics in Columbian ground squirrels. *Can. J. Zool.* 63:2095–2104.
84. **Dobson, F.S. and Kjelgaard, J.D.** 1985b. The influence of food resources of life history in Columbian ground squirrels. *Can. J. Zool.* 63:2105–2109.
85. **Zucker, I. and Licht, P.** 1983a. Circannual and seasonal variations in plasma luteinizing hormone levels of ovariectomized ground squirrels (*Spermophilus lateralis*). *Biol. Reprod.* 28:178–185.
86. **Zucker, I. and Licht, P.** 1983b. Seasonal variations in plasma luteinizing hormone levels of ovariectomized ground squirrels (*Spermophilus lateralis*). *Biol. Reprod.* 29:278–285.
87. **Hikim, A.P.S., Hikim, I.S., Amador, A.G., Bartke, A., Wolf, A. and Russell, L.D.** 1991. Reinitiation of spermatogenesis by exogenous gonadotropins in a seasonal breeder, the woodchuck (*Marmota monax*), during gonadal inactivity. *Am. J. Anat.* **192:194–213.**
88. **Barnes, B.M., Licht, P. and Zucker, I.** 1987. Temperature-dependence of in vitro androgen production in testes from hibernating ground squirrels, *Spermophilus lateralis*. *Can. J. Zool.* 65:3020–3023.
89. **York, A.D.** 1990. Effect of winter high temperatures on reproduction and circannual rhythms in hibernating ground squirrels. *J. Biol. Rhythms* 5:119–130.
90. **Mrosovsky, N.** 1990. Circannual cycles in golden-mantled ground squirrels: fall and spring cold pulses. *J. Comp. Physiol. Neuroethol. Sensory and Neural Behav. Physiol.* 167:683–689.
91. **Dark, J., Ruby, N.F., Wade, G.N., Licht, P. and Zucker, I.** 1992. Accelerated reproductive development in juvenile male ground squirrels fed a high-fat diet. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 262:644–650.
92. **Licht, P., Zucker, I., Hubbard, G. and Boshes, M.** 1982. Circannual rhythms of plasma testosterone and luteinizing hormone levels in golden-mantled ground squirrels (*Spermophilus lateralis*). *Biol. Reprod.* 27:411–418.
93. **Khan, U.W. and Rai, U.** 2007. Differential effects of histamine on Leydig cell and testicular macrophage activities in wall lizards: Precise role of H1/H2 receptor subtypes. *J. Endocrinol.* (online) www.endocrinology.org
94. **Concannon, P.W., Baldwin, B., Lawless, J., Hornbuckle, W. and Tennant, B.** 1983. Corpora lutea of pregnancy and elevated serum progesterone during pregnancy and postpartum anestrus in woodchucks (*Marmota monax*). *Biol. Reprod.* 29:1128–1134.
95. **Holekamp, K.E., Nunes, S. and Talamantes, F.** 1988. Patterns of progesterone secretion in free-living California ground squirrels (*Spermophilus beecheyi*). *Biol. Reprod.* 105:1051–1059.
96. **Foreman, D. and Garris, D.** 1984. Plasma progesterone levels and corpus luteum morphology in the female prairie dog (*Cynomys ludovicianus*). *Gen. Comp. Endocrinol.* 55:315–22.
97. **Einspanier, A., Nubbemeyer, R., Schlote, S., Schumacher, M., Ivell, R., Fuhrmann, K. and Marten, A.** 1999. Relaxin in the marmoset monkey: secretion pattern in the ovarian cycle and early pregnancy. *Biol. Reprod.* 61:512–520.
98. **Blumstein, D.T. and Armitage, K.B.** 1999. Cooperative breeding in marmots. *Oikos* 84:369–382.
99. **Hacklander, K., Mostl, E. and Arnold, A.** 2003. Reproductive suppression in female alpine marmots, *Marmota marmota*. *Anim. Behav.* 65:1133–1140.
100. **Michener, G.R.** 1982. Infanticide in ground squirrels. *Anim. Behav.* 30:936–938.
101. **Blumstein, D.T.** 1997. Infanticide among golden marmots. *Ecol. Ethol. Behav.* 9:169–174.
102. **Hacklander, K. and Arnold, W.** 1999. Male-caused failure of female reproduction and its adaptive value in alpine marmots. *Behav. Ecol.* 10:592–597.
103. **Boonstra, R. and McColl, C.J.** 2000. Contrasting stress response of male arctic ground squirrels and red squirrels. *J. Exp. Zool.* 286:390–404.
104. **Mateo, J.M.** 2006. Developmental and geographic variation in stress hormones in wild Belding's ground squirrels (*Spermophilus beldingi*). *Horm. Behav.* 50:718–725.
105. **Byrom, A.E., Karels, T.J., Krebs, C.J. and Boonstra, R.** 2000. Experimental manipulation of predation and food supply of arctic ground squirrels in the boreal forest. *Can. J. Zool.* 78:1309–1319.
106. **Shivatcheva, T.M., Ankov, V.K. and Hadjioloff, A.I.** 1988. Circannual fluctuations of the serum cortisol in the European ground squirrel, *Citellus citellus* L. *Comp. Biochem. Physiol.* 90:515–518.
107. **Kenagy, J.G. and Place, N.J.** 2000. Seasonal changes in plasma glucocorticosteroids of free-living female yellow-pine chipmunks: effects of reproduction and capture and handling. *Gen. Comp. Endocrinol.* 117:189–199.
108. **Boonstra, R., Hubbs, A.H., Lacey, E.A. and McColl, C.J.** 2001. Seasonal changes in glucocorticoid and testosterone concentrations in free-living arctic ground squirrels from the boreal forest of

- the Yukon. *Can. J. Zool.* 79:49–58.
109. **Hik, D.S., McColl, C.J. and Boonstra, R.** 2001. Why are Arctic ground squirrels more stressed in the boreal forest than in alpine meadows? *EcoSci.* 8:275–288.
110. **Place, N.J.** 2000. Effects of experimentally elevated testosterone on plasma glucocorticoids, body mass, and recapture rates in yellow-pine chipmunks, *Tamias amoenus*. *J. Exp. Zool.* 287:378–383.
111. **Karsch, F.J., Robinson, J.E., Woodfill, C.I. and Brown, M.B.** 1989. Circannual cycles of luteinizing hormone and prolactin secretion in ewes during prolonged exposure to a fixed photoperiod: evidence for an endogenous reproductive rhythm. *Biol. Reprod.* 41:1034–1046.
112. **Hastings, M. H., Herbert, J., Martensz, N.D. and Roberts, A.** 1985. Annual reproductive rhythms in mammals: mechanisms of light synchronization. *Ann. NY Acad. Sci.* 453:182–204.
113. **Lee, T.M. and Zucker, I.** 1995. Seasonal variations in circadian rhythms persist in gonadectomized golden-mantled ground squirrels. *J. Biol. Rhythms* 10:188–195.
114. **Prendergast, B.J., Nelson, R.J. and Zucker, I.** 2002. Mammalian seasonal rhythms behavior and neuroendocrine substrates. *Horm. Brain Behav.* 2:93–110.
115. **Heibert, S.M., Thomas, E.M., Lee, T.M., Pelz, K.M., Yellon, S.M. and Zucker, I.** 2000. Photic entrainment of circannual rhythms in golden-mantled ground squirrels: role of the pineal gland. *J. Biol. Rhythms* 15:126–134.