Mild $Pd(OAc)_2/PPh_3$ Catalyzed Cyclization Reactions of 2-Vinylazetidines with Heterocumulenes: An Atom-Economy Synthesis of Tetrahydropyrimidinone, Tetrahydropyrimidinimine, and Thiazinanimine Analogs

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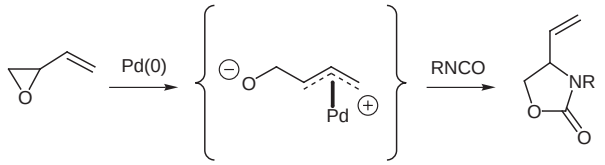
Dedicated to Professor Ryoji Noyori − a remarkable person; a cherished friend; a truly exceptional scientist, with an extraordinary number of landmark contributions to research and innovation.

Abstract: A versatile method for the reaction of *N*-alkyl-2-vinylazetidines with heterocumulenes has been established using a $Pd(OAc)_2/PPh_3$ catalyst system at room temperature. Minor modifications in the design of either substrate allowed for the optimization of product yield. Evidence for π-allylpalladium formation was obtained from the reaction of *trans*-1-butyl-4-methyl-2-vinylazetidine, which afforded a *cis*/*trans* mixture of products arising from stereochemical inversion through η^3-η^1-η^3 isomerization.

Key words: tetrahydropyrimidin-2-ones, tetrahydropyrimidin-2-ylidenes, [1,3]thiazinan-2-ylidenes, pi-allylpalladium complexes

Introduction

An advance in heterocyclic chemistry was the design of cycloaddition reactions between strained rings and carbon electrophiles, exemplified by the synthesis of oxazolidin-2-ones from oxiranes and isocyanates.[1] At elevated temperatures (50-140 °C), research had evolved a variety of catalysts[2] that effect the reactions of strained heterocycles with heterocumulenes, via an assortment of related organometallic intermediates and with reasonably good regiochemical control[2d] and some examples of stereospecificity.[2f] In general, the inability to adapt these methods to a broad range of substrates limited their acceptance, and there were no means for enantioselectivity. However, the presence of a vinyl substituent adjacent to the heteroatom of the strained ring system enabled vast improvements.[3] Using zerovalent palladium catalysts, the reactions proceeded at ambient temperature and pressure due to the facile formation of π-allyl intermediates, the active species for insertion (Scheme 1). These intermediates introduced excellent regioselectivity and the potential for stereoselectivity, where the catalyst complex contains optically active phosphines.



Scheme 1

Techniques for palladium-catalyzed insertions were successfully applied to oxirane[3a-d,f] and oxetane[3e] substrates, incorporating isocyanates,[3a-c,e] carbodiimides,[3c,e] imines,[3f] and activated olefins[3d] for insertion. Asymmetric procedures were developed in the reactions of vinyloxiranes with heterocumulenes using BINAP and TolBINAP ligands.[3] Furthermore, this design proved stereoselective in the preparation of benzo[1,3]oxazinanes from bicyclic oxetane derivatives.[3e] Both aryl- and alkyl-substituted heterocumulenes were suitable for the insertion,[3a,b] and various functional groups could be tolerated in the reactions.[3a-f] Additionally, Trost et al. implemented procedures for the cleavage of certain aryl groups in the products,[3a] establishing the value of this methodology to synthetic organic chemistry.

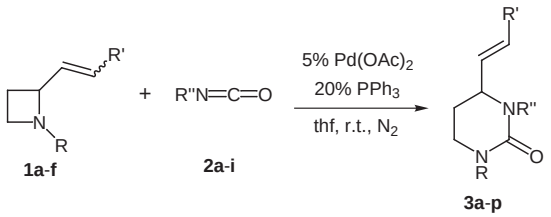
In contrast, however, no methods have been adapted to reactions of 2-vinylazetidines with heterocumulenes despite feasible routes to these compounds[4] and research that substantiates formation of the analogous π-allylpalladium complexes from the nitrogen heterocycles.[5,6] Yamamoto et al. reported palladium-catalyzed rearrangements of 2-vinylazetidines, 4-vinylazetidinones, and related derivatives, which could only be explained through formation of the cognate π-allyl complex.[5c] Moreover, similar approaches have been employed in the carbonylation of vinylaziridines for applications to β-lactam chemistry[5d,e] and in the synthesis of tetrahydrofuran and piperidine derivatives from the rearrangement of dienyl-substituted aziridines and azetidines.[5b]

Therefore, it was anticipated that an examination of the previously unstudied palladium-catalyzed reaction between 2-vinylazetidines and heterocumulenes would afford interesting heterocyclic products, and could initiate the development of new methodologies for inserting other carbon electrophiles.

Results and Discussion

Reactions of *N*-Alkyl-2-Vinylazetidines with Isocyanates. In the absence of a catalyst, the reaction of 2-vinylaziridines with heterocumulenes afforded no conversion to the expected five-membered heterocycle – a transformation that proceeded with zerovalent palladium present.[6]

Therefore, synthesis of the six-membered products from the related reactions of 2-vinylazetidines would require a palladium complex as the catalyst. Previously, many palladium-phosphine systems demonstrated proficiency in the reactions of vinyloxiranes[3a-d,f] and −oxetanes,[3e] carbonylations of vinylaziridines,[5d,e] and for the ring opening of 2-vinylazetidines.[5b,c] Therefore, an examination of these systems was undertaken, using the room temperature reaction of *N*-alkyl-2-vinylazetidines and arylisocyanates as the standard. $Pd_2(dba)_3{\cdot}CHCl_3$ with bis-phosphine ligands displayed lower activity than anticipated. Studies have determined that dibenzylideneacetone can adversely affect reactions by remaining chelated to the metal center in the presence of phosphines and hindering the formation of the active catalyst complex.[7] Consequently, the palladium species was replaced with $Pd(PPh_3)_4$, which exhibited better results, but inconsistencies were apparent due to the sensitive nature of this compound. Thus the catalyst was prepared in situ by stirring palladium (II) acetate and triphenylphosphine in dry, degassed solvent to ensure high catalyst purity. The conversion of these reactions (Scheme 2) became essentially quantitative upon GC analysis with this system.



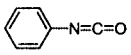
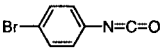
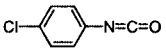
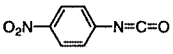
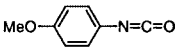
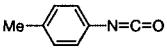
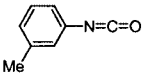
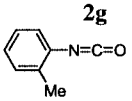
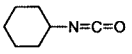
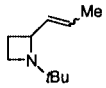
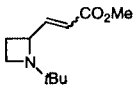
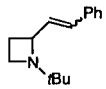
Scheme 2

Optimum catalyst efficiency was observed at 5 mol% of $Pd(OAc)_2$ with a 1:4 ratio of catalyst to ligand, and afforded a highly general system for the reaction of *N*-alkylated 2-vinylazetidines with isocyanates (Table 1) under mild conditions.

All the reactions employing phenylisocyanate essentially proceeded with quantitative conversion. Longer reaction times (entries 14 and 16), indicative of less reactive azetidine species, often resulted in lower yields due to the competing trimerization[2b] of **2a**. Identifying features in the NMR spectra characteristic of the tetrahydropyrimidin-2-ones were the vinyl protons between 5 ppm and 6 ppm, the C_4 hydrogen at ~4 ppm, and the carbonyl carbon at 154 ppm. A strong signal at 1649-1620 cm^{-1}, typical of urea carbonyls, was present in the IR spectra of **3**.

Entries 1, 10, and 11 demonstrate the effect of the alkyl chain on the azetidine substrate. When employing the cyclohexyl (**1a**) and *tert*-butyl (**1c**) derivatives, the reactions were longer with an apparent reduction in product yields, indicating a possible steric dependency for these reactions. Less bulky substrates, such as **1b**, exhibited excellent reactivity. Hindrance by the *N*-alkyl group would be important in the incipient attack on the heterocumulene and subsequent ring closing.

Table 1 Pd(0)-catalyzed reactions[a] of 2-vinylazetidines with isocyanates at ambient temperature and pressure.

Entry	Azetidine	Isocyanate	Time[b] (h)	Product	Yield[c] %
1	 **1a**	 **2a**	2	**3a**	89
2	**1a**	 **2b**	2	**3b**	95
3	**1a**	 **2c**	2.5	**3c**	90
4	**1a**	 **2d**	2	**3d**	66
5	**1a**	 **2e**	3	**3e**	89
6	**1a**	 **2f**	3.5	**3f**	93
7	**1a**	 **2g**	2	**3g**	97
8	**1a**	 **2h**	3.5	**3h**	70
9	**1a**	 **2i**	6	**3i**	73
10	 **1b**	**2a**	1	**3j**	97
11	 **1c**	**2a**	3.5	**3k**	89
12	**1c**	**2b**	2.5	**3l**	91
13	**1c**	**2e**	3	**3m**	87
14	 **1d**	**2a**	5.5	**3n**	70
15	 **1e**	**2a**	2	**3o**	98
16	 **1f**	**2a**	6	**3p**	67

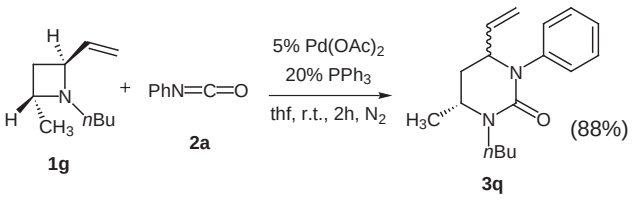
[a] PPh_3 and $Pd(OAc)_2$ were premixed for 30 min in 4.0 mL of dry, degassed THF followed by addition of 1.0 mmol of **1** and **2** with 1.0 mL of dry THF; [b] indicated by consumption of substrates (gas chromatography); [c] purified by column chromatography with ether/pentane.

To investigate any electronic influence, monosubstituted arylisocyanates supplanted **2a** for insertion (entries 2-8 and 12-13). No tangible trend could be identified from these reactions since affecting the electrophilicity of the central carbon would inevitably influence the capacity for trimerization of the heterocumulene. However, interesting results were obtained and demonstrated how the isocyanate substrate can be modified to optimize product formation. Highly electron-withdrawing substituents, such as the *p*-nitro group in **2d**, increased the reactivity of the isocyanate but caused greater polymerization. Thus, even though the rate of the reaction was quite rapid, a low yield of **3d** was acquired. Prior examples using aryl heterocumulenes possessing this group in palladium-catalyzed reactions with vinyloxiranes have been unsuccessful,[3] and this result can still be considered an accomplishment. Interestingly, similar reactivity to **2a** was observed for **2c**, **2e**, and **2f** (entries 3, 5-6, and 13), whereas more subtle modifications, as in **2b** and **2g**, enhanced the insertion of the heterocumulene (entries 2 and 7). Presumably the *p*-bromo and *m*-methyl substituents electronically tailored the substrate for preferential nucleophilic attack. Sufficient electrophilicity was present to optimize product synthesis, but not enough to activate the isocyanate for trimerization. Additionally, entry 9 confirms that alkylisocyanates are sufficiently reactive as **3h** was obtained in good yield.

An unexpected consequence from the reaction with **2h**, *o*-tolylisocyanate, arose from the great steric demand that this substrate imposed in the product. Along with reducing the overall yield of **3h**, an energy barrier was created between configurations of the heterocycle that could not be overcome at room temperature. Hence, a doubling of the ^{1}H and ^{13}C NMR spectra occurred due to slight chemical shift differences between the exchanging hydrogens and carbons, causing a ~2:1 ratio of the conformers that originates from a slow equilibrium in solution. 2D EXSY and variable temperature NMR experiments reinforced these findings. The related tetrahydropyrimidin-2-ones presumably possess the equilibrium, but it would be much faster and result in an averaging of chemical shift values. Therefore, the *ortho*-methyl group is probably responsible for the energy barrier.

Continuing with the study of electronic effects, derivatives of the azetidine substrate **1c** were prepared and reacted with phenylisocyanate (entries 14-16). In addition to demonstrating some influence on the reactivity of the 2-vinylazetidine, these examples displayed tolerance for substituents on the vinyl group in these reactions, which is important for the adaptation of such processes to practical organic synthesis. For each of these azetidines (**1d-f**), a mixture of *E* and *Z* isomers was prepared, but only the *E* configuration resulted in **3n-p**, demonstrating selectivity due to steric congestion. Electron-withdrawing substituents (e.g. **1e**) increased the reactivity of the 2-vinylazetidine by removing electron density from the moiety and enhancing the polarization of the ring C-N bond. Therefore, oxidative addition to the palladium catalyst was improved, facilitating formation of the π-allyl intermediate, the active species for the room temperature cyclization with heterocumulenes. In contrast, the inductive effect of the methyl group in **1d** deactivated the 2-vinylazetidine retarding oxidative addition to the metal. There would be less of the π-allylpalladium moiety present during the reaction, causing conversion to be lethargic and allowing for some trimerization of **2a**. The reaction of **1f** proceeded with similar kinetics and product yield as **1d**, even though the phenyl group would impart greater steric hindrance than the methyl group. Thus, the phenyl group must be activating **1f** in the same fashion as the carbomethoxy substituent in **1e**, but the bulkiness of the compound hindered reactivity, and trimerization again became appreciable. Consequently, the highest yields can be achieved by substituting the vinyl group with less bulky, electron-withdrawing functionalities.

Baeg et al. reported that the palladium(II)-catalyzed cycloaddition reactions of *trans*-1-butyl-2-carbomethoxy-4-methylazetidine with diarylcarbodiimides proceeded with retention of configuration.[2f] In contrast, since palladium(0)-catalyzed reactions are hypothesized to ring cleave the strained heterocycle, the π-allyl moiety that forms can induce stereochemical scrambling. Thus, the related 2-vinylazetidine (**1g**) was prepared and reacted with **2a** (Scheme 3) to determine the stereospecificity of these reactions.

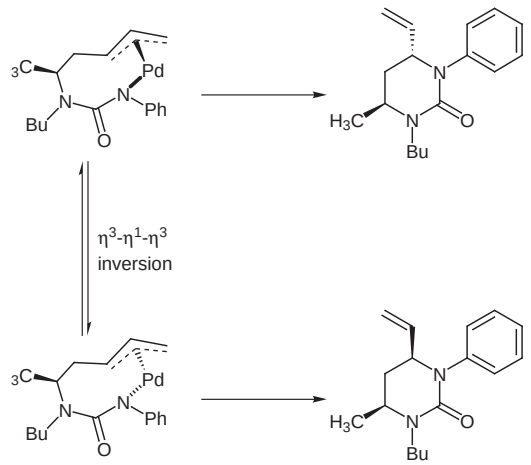


Scheme 3

The ^{1}H and ^{13}C NMR spectra of **3q** revealed a mixture of stereochemical isomers (confirmed by nOE experiments as a 1:2 composition of *cis*:*trans*), verifying that scrambling had occurred in accordance with previous results.[3a,6] This effect can be explained by the formation of a π-allylpalladium intermediate and isomerization via an η^3-η^1-η^3 inversion (Scheme 4).

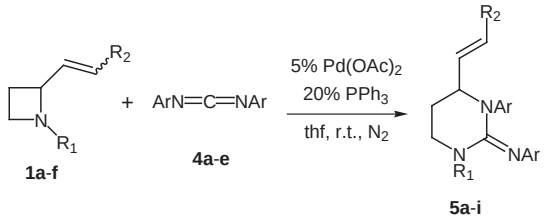
Supplementing the facile nature of these reactions to proceed under mild conditions with a Pd(0) catalyst, this evidence supports the postulated π-allyl intermediate. Therefore, it should be possible to apply this procedure to the insertion of other heterocumulenes.

Reactions of *N*-Alkyl-2-Vinylazetidines with Diarylcarbodiimides and Arylisothiocyanates. Procedures should display good versatility for practical organic synthesis. Therefore, other heterocumulene compounds were tested as substrates. Carbodiimides are known to exhibit



Scheme 4

comparable electrophilicity to isocyanates,[8] and previous reports demonstrate better results in reactions of these heterocumulenes with vinyloxiranes[3c] and −oxetanes.[3e]

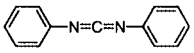
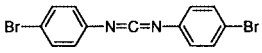
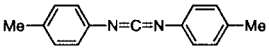
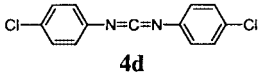
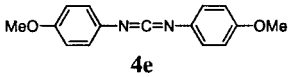
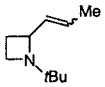
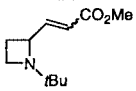


Scheme 5

However, the substituent on the nitrogen will increase the steric congestion introduced by the diarylcarbodiimides, which likely impeded the initial nucleophilic attack and resulted in longer reaction times (Table 2).

Fortunately the polymerization of carbodiimides does not occur as readily,[8] and the synthesis of **6** was generally unaffected by the slower kinetics. Purification of the tetrahydropyrimidin-2-ylidenes proved more difficult, however, which is apparent in the reported yields. ^1H and ^{13}C NMR spectra, which displayed signals between 5 ppm and 6 ppm characteristic of the vinyl protons, a broad multiplet

Table 2 Pd(0)-catalyzed reactions[a] of 2-vinylazetidines with mono-substituted diarylcarbodiimides at ambient temperature and pressure.

Entry	Azetidine	Diarylcarbodiimide	Time[b] (h)	Product[c]	% Yield
1	 **1a**	 **4a**	18	**5a**	86
2	**1a**	 **4b**	18	**5b**	92
3	**1a**	 **4c**	18	**5c**	83
4	 **1b**	**4a**	10	**5d**	94
5	 **1c**	**4a**	20	**5e**	75
6	**1c**	 **4d**	21	**5f**	70
7	**1c**	 **4e**	20	**5g**	76
8	 **1d**	**4a**	48	**5h**	39[d]
9	 **1e**	**4a**	45	**5i**	92

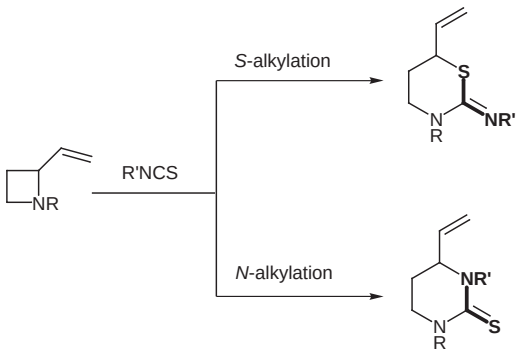
[a] PPh_3 and $Pd(OAc)_2$ were premixed for 30 min in 4.0 mL of dry, degassed THF followed by addition of 1.0 mmol of **1** and **4** with 1.0 mL of dry THF; [b] indicated by consumption of substrates (gas chromatography); [c] purified by column chromatography with ether/pentane; [d] 51% conversion, as calculated from recovery of **4a**.

at ~4.0 ppm of the C_4 hydrogen, and a peak at ~151 ppm for the imine carbon, supported the identification of these products. The IR spectra featured a strong absorbance around 1596-1571 cm^{-1}, substantiating the presence of an imine.

The effect of the alkyl chain on **1** became more evident from these experiments. By comparing entries 1, 4, and 5 in Table 2, a gradient of reactivity can be established where $1^o > 2^o > 3^o$, which originates principally through steric influence. As with the insertion of isocyanates, electronic properties of both substrates demonstrated some sway over the product yield. The *p*-bromo substituent (entry 2) apparently increased reactivity and enhanced the formation of **5b**, but no obvious trends were evident with monosubstituted diarylcarbodiimides. The reaction was unsuccessful with DCC, a dialkyl derivative, but the large steric congestion imposed by the cyclohexyl groups could have induced this result.

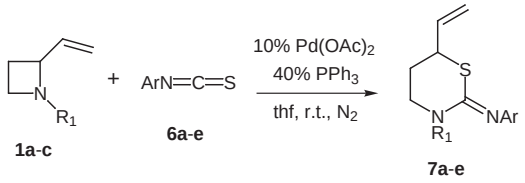
Modification of the vinyl group in the azetidine substrate (entries 8-9) affected reactions with **4a**. The 1-propenyl derivative, **1d**, severely retarded the reaction, limiting the conversion to only 51% after 2 days and affording a modest yield of the tetrahydropyrimidin-2-ylidene. However, **5i** was obtained in excellent yield, suggesting that electron-withdrawing moieties facilitate formation of the π-allylpalladium intermediates and promote the insertion of the heterocumulene. Again, only the *E* isomers of **5h-i** were prepared, which provided further evidence for the formation of the π-allyl intermediate.

The palladium-catalyzed cyclization was also applied to reactions of 2-vinylazetidines with isothiocyanates. Reduced electrophilicity of the isothiocyanate group[8] gave lower conversion and both *S*- and *N*-alkylation occurred in the cyclization of the presumed π-allyl intermediates (Scheme 6).



Scheme 6

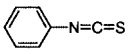
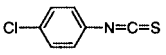
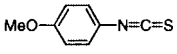
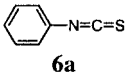
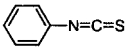
From their studies with 2-vinyloxiranes, Trost et al. suggested that isocyanate insertion could result in either *O*- or *N*-alkylated products, but that upon further exposure to zerovalent palladium, the former isomerized to the *N*-alkylated heterocycle.[3a] Therefore, by increasing the catalyst load and maintaining a 1:4 ratio of catalyst to ligand (Scheme 7), only **7** was recovered from the isothiocyanate reactions and the yields were improved (Table 3).



Scheme 7

The [1,3]thiazinan-2-ylidenes displayed a comparable signal at ~151 ppm in the ^{13}C NMR spectra and a stretching frequency in the IR at 1575 cm^{-1} - comparable to those of **5** - confirming that the reaction had afforded the imine product. A signal at ~180 ppm in the ^{13}C NMR spectra would be expected, denoting the thiocarbonyl, if *N*-alkylation had predominated. The ^1H NMR spectra again displayed the characteristic vinyl signals while the chemical shift of the C_4 hydrogen decreased by 0.2-0.3 ppm due to greater shielding by the adjacent sulfur atom.

Table 3 Pd(0)-catalyzed reactions[a] of 2-vinylazetidines with monosubstituted arylisothiocyanates at ambient temperature and pressure.

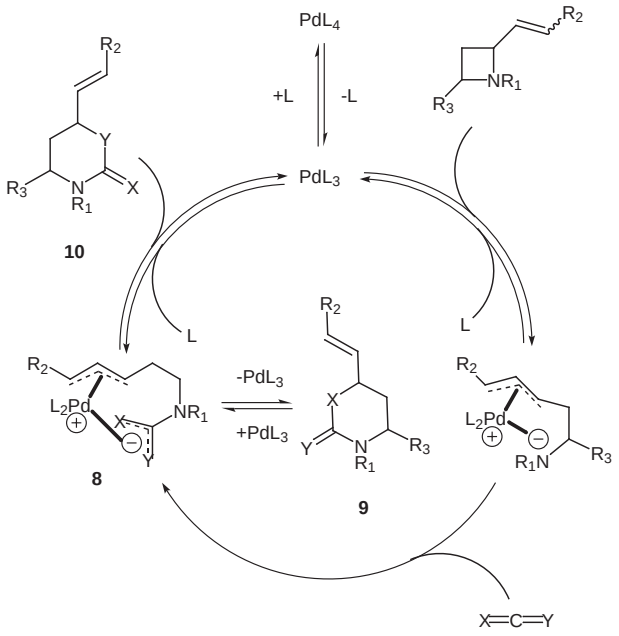
Entry	Azetidine	Isothiocyanate	Time[b] (h)	Product[c]	Yield %
1	 **1a**	 **6a**	20	**7a**	95
2	**1a**	 **6b**	20	**7b**	90
3	**1a**	 **6c**	20	**7c**	94
4	 **1b**	 **6a**	7	**7d**	92
5	 **1c**	 **6a**	48	**7e**	47[d]

[a]PPh_3 and $Pd(OAc)_2$ were premixed for 30 min in 4.0 mL of dry, degassed THF followed by addition of 1.0 mmol of **1** and **6** with 1.0 mL of dry THF; [b]indicated by consumption of substrates (gas chromatography); [c]purified by column chromatography with ether/pentane; [d]48% conversion, as calculated from recovery of **6a**.

Functional group tolerance is shown by the results in entries 2 and 3, but aryl substitution appeared to have little influence on the reactivity of the isothiocyanate. Upon examination of the reaction times for **1a-c** with phenylisothiocyanate (entries 1, 4, and 5), the same trend was evident – increasing the bulk of the nitrogen substituent on the 2-vinylazetidine diminished reactivity because of the heightened steric hindrance. The insertion of the isothiocyanate into the π-allylpalladium moiety requires

the *N*-aryl group of **6** to be in close proximity to the *N*-alkyl group of **1**. For **1c**, the congestion would be quite high, sufficiently restricting the formation of this product-yielding intermediate, and the conversion declined significantly.

A possible catalytic cycle is outlined in Scheme 8, based on these reactions and prior reports.[3,5] The oxidative cleavage of 2-vinylazetidines was speculated to proceed in a facile and reversible manner, affording a reactive π-allylpalladium complex. Varying the R′ group of the azetidine influences this equilibrium, whereby electron-withdrawing groups favor formation of the π-allyl complex and enhance the reaction. In all likelihood, nucleophilic attack on the heterocumulene to form **8** is the rate-limiting step. The greater steric hindrance of carbodiimides and lower electrophilicity of isothiocyanates impeded this step, which caused slower kinetics compared with reactions involving isocyanates. Two potential products can be initially formed by the cyclization of **8** when isocyanates and isothiocyanates are the heterocumulene substrate. Recent accounts have established that five-membered heterocycles possessing vinyl substituents adjacent to a heteroatom are susceptible to ring opening.[9] Therefore, it is postulated that **9** and **10** can reform intermediate **8**, and the equilibrium eventually affords only the thermodynamically favored product, **10**.



Scheme 8

Conclusion

Tetrahydropyrimidin-2-ones, tetrahydropryimidin-2-ylidenes, and [1,3]thiazinan-2-ylidenes were prepared in good to high yields and with excellent regioselectivity, under mild conditions, from the palladium(0)-catalyzed reaction of *N*-alkylated 2-vinylazetidines with aryl- and alkylisocyanates, diarylcarbodiimides, and arylisothiocyanates. A catalytic cycle was proposed involving a reactive π-allyl intermediate and featuring a likely equilibrium between kinetic and thermodynamic products via cyclization in the product-forming step. The generality of this method indicates that other carbon electrophiles could be inserted into the enabling one to synthesize an assortment of heterocycles.

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Supporting information is available on request from the publisher.

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